

# Economic Geology

and the  
Bulletin of the Society of Economic Geologists

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# Economic Geology

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ECONOMIC GEOLOGISTS

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# ECONOMIC GEOLOGY

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VOL. XL

MAY, 1945

No. 3

## PROBLEMS OF THE PERENNIAL YIELD OF ARTESIAN AQUIFERS.<sup>1</sup>

O. E. MEINZER.

THERE is a sharp distinction between typical *phreatic* or water-table conditions and typical *piezic* or artesian conditions. Where water-table conditions exist, the aquifer is only partly filled with water and the water level in wells indicates the upper surface of the zone of saturation. On the other hand, where artesian conditions exist, the aquifer is entirely filled and the water presses upward against a confining bed and will rise in wells to some level above the top of the aquifer. When a water-table well is pumped unwatering occurs, but when an artesian well is pumped or discharges by artesian flow there is no unwatering, at least in the early stages of discharge.

The hydrostatic theory of artesian pressure was understood in Italy as early as the Seventeenth century, before the emergence of geology, and some of the earliest work in geology involved its application to artesian basins in Italy and France. Quantitative studies in ground water, however, for a long time related chiefly to water-table conditions, both in Europe and in the United States (5).

Quantitative studies of artesian aquifers involve the law of flow through water-bearing materials. Darcy's law of direct variation with hydraulic gradient was announced in 1856 (2). We believe that it has been thoroughly confirmed, as for example by the work of Reynolds (7) and Slichter (8) and the recent work of Fishel, Tolman, Poland, and others (4, 12). We are building our quantitative work, with much assurance, on this law—determining permeability and storage coefficients chiefly by discharging-well tests.

In 1863, Dupuit (3) published the results of his pioneer studies on the hydraulics of wells, based on Darcy's law and on the assumption of a pumped well at the center of a circular island. The formula that he developed has been widely published in the hydrologic literature, but very little use has been made of it, because (1) the formula forecasts the yield of a well when the permeability of the aquifer is known, whereas practically it is less difficult

<sup>1</sup> Published with the permission of the Director of the Geological Survey, U. S. Department of the Interior.

to sink a well and pump it than to determine the permeability, and (2) the formula includes the radius of the well ( $r$ ) and the radius of the cone of depression ( $R$ ), but the effective radius of the well may be much greater than the radius of the actual drill hole, and the cone of depression may expand almost indefinitely as pumping progresses.

Adolph Thiem developed the method of determining the rate of flow of ground water by placing a salt into a well and observing the time required for the salt to reach one or more downstream wells. The method was later used in this country by Slichter, who improved it by detecting the salt with electric conductivity apparatus instead of titrating for chloride. Günter Thiem, son of Adolph, visited the United States early in this century and observed Slichter's work on Long Island. In 1906 he published his doctor's thesis, in which he developed the first discharging-well method (9). He re-organized the Dupuit formula in such a way as to put it to practical use by measuring the rate of discharge of a pumped well and solving for permeability, and by using the drawdowns in two observation wells at distances  $r_1$  and  $r_2$ , instead of the indeterminate quantities represented by  $r$  and  $R$ . This formula has been used by Thiem since that time in his extensive consulting practice and was his principal method of quantitative investigation when I visited him in his home in Leipzig in 1936.

The progress that has recently been made in the investigation of artesian aquifers is based largely on three achievements—the recognition of the principle of compressibility and elasticity of artesian aquifers in 1924, the Grand Island test in 1931, and the development of the non-equilibrium formula in 1935.

In reviewing the work of Hard in North Dakota in 1924, conclusive evidence was found that, according to the laws of fluid mechanics, the phenomena of artesian wells show that the artesian aquifers are compressible and, moreover, possess significant amounts of volume elasticity (6). It is now known that when an artesian well first discharges, its water is all derived from storage by compression of the aquifer (and expansion of the water), and that a large part of the total production of some aquifers, such as the Dakota sandstone, has come from storage by compression of the aquifer and associated fine-grained beds. In the tests of artesian aquifers we now usually compute the coefficient of storage, which indicates the yield from storage for each unit of reduction in head. The principle of compressibility and elasticity introduces time as a factor.

The test made by Wenzel (14 and 16) in 1931 near Grand Island, Nebr., was on an aquifer having water-table conditions, but it produced results that are important in the study of artesian aquifers. With nearly 10,000 measurements, on more than 80 observation wells, it became possible to determine precisely what happened as the pumping proceeded. The data showed that equilibrium, or steady-flow, conditions are approximated near the discharging well while the cone of depression is still expanding, and that the Thiem formula should be applied only after the circle of steady flow has expanded beyond the observation wells. Moreover, the data for the pre-equilibrium period were used to compute the coefficient of storage (specific yield under

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water-table conditions), and by extrapolation to determine approximately the coefficient of permeability. Thus a non-equilibrium method was devised.

In 1935 Theis (10) investigated the hydraulics in the vicinity of a discharging well before equilibrium, or steady flow, is reached. By using the mathematical work that had been done on analogous thermal conditions, he developed a formula, and later a graphic method, for determining coefficients of permeability and storage under non-equilibrium conditions. This formula, applied to artesian aquifers, depends on the elasticity of the aquifers and it involves time as a variable. Starting with this fundamental formula, it has been found possible to devise methods for determining one or both of the coefficients under a variety of layouts of pumped and observation wells and by varying the rates of pumping in one or more of the wells. Because of its adaptability as well as its demonstrated reliability, the Theis non-equilibrium method, in its various forms, is now being used extensively, especially in developing water supplies for war purposes.

This review brings us to the main purpose of this paper, to show that while the methods now in use appear to be reliable for the immediate future (which is our concern where war uses are involved), the ultimate destiny of many of the important artesian aquifers is still in question. The uncertainties relate largely to the long-term coefficients of storage and to the encroachment of salt water. Associated with these are limitations imposed by the lateral extent and structural irregularities of the aquifer and the potential rate of recharge in the intake area, which are not discussed in this brief paper.

In a reinvestigation of the Dakota sandstone in North Dakota by Wenzel and Sand (15), the computations as of 1938 confirm the conclusions reached 15 years earlier to the effect that most of the water discharged by the artesian wells has been obtained from storage, although practically no decline in water level has occurred at the western outcrop, which is the intake area. The computations showed, however, that with the diminished discharge, a balance is being approached between withdrawal and recharge, the natural discharge at the low eastern end of the formation being captured by the artesian wells. Systematic data have been obtained on pumpage and water levels in the Atlantic City area during the last 20 years. It was shown by Thompson (11) and by Barksdale and others (1) that in the early years of record there was a progressive decline of water level with the seasonal recurrence of pumping at a given rate, apparently due chiefly to withdrawal from storage. A careful study of all the data now available should give indication as to any trend toward cessation of this decline and, therefore, as to the perennial yield by recharge. In the Santa Clara Valley, Calif., according to Tolman and Poland (13), about 15 per cent of the large quantity of water pumped from 1919 to 1937 was obtained from storage by compression.

The perennial yield may be affected by compression in two other ways: (1) The compression of the water-bearing material may reduce its permeability; and (2) if the aquifers lose their resilience as a result of the alternate decrease and increase in artesian pressure, they will also lose their capacity for temporary storage near wells that are pumped intermittently and the water levels will decline more rapidly when the wells are pumped.

In Santa Clara Valley the maximum subsidence of the land surface due to pumping from wells has amounted to about 5 feet. Tolman and Poland (13) showed that the sinking occurred in areas of heavy well production that have artesian conditions and confining beds of dense clay. They concluded that the compression has occurred chiefly in the clay deposits, which have contributed their water to the water-bearing sand and gravel; and that with restoration of the artesian pressure, recovery will depend largely on whether the structure and composition of the clay have been changed by the compression.

Our present view is that the water delivered from storage by an artesian aquifer through prolonged withdrawal has come first from the aquifer itself and later but in larger volume from the associated silt and clay beds; therefore, that there has been relatively little compression of the aquifer and hence little reduction in its permeability; further, that with restored artesian pressure, the compression of the clay beds may prove to be nearly permanent, the silt beds may recover to a large extent but with considerable lag (perhaps adapted for annual cycles of pumping), and the more permeable water-bearing sands may recover promptly and nearly completely, so that the resilience will be retained which is shown by the aquifer when pumping on individual wells is started or stopped.

There are two principal methods for investigating encroachment of salt water—(1) determining the form of the piezometric surface of the aquifer to ascertain whether there is a hydraulic gradient from the salt water to the wells; and (2) testing for chloride in samples of water taken periodically from producing wells or from pilot wells located nearer to the area of salt water or extending down nearer to underlying salt water.

The artesian wells at Atlantic City are situated on land that is completely surrounded by salt water, the aquifer is overlain and underlain by salt water, several million gallons have been pumped from these wells daily through a period of a few decades, and the head has been drawn down far below sea level. Yet in 1924 the water tested only 11 parts per million of chloride, and in 1943 it tested only 10 parts. Nevertheless, water of higher chloride content may be moving toward the wells, and ultimately there may be at least some measure of salt contamination.

In 1941 a survey of the whole country was made by the Ground Water Division with respect to the encroachment of salt water. The results, presented in 28 papers at a conference in Washington, show that relatively little encroachment has thus far occurred but that possibilities exist for more serious damage with the current or increased rates of withdrawal.

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January 27, 1944.



## GROUND-WATER EXPLORATION AT ALEXANDRIA, LOUISIANA.<sup>1</sup>

JOHN C. MAHER AND PAUL H. JONES.

### ABSTRACT.

Serious overdevelopment of the ground-water supply in Alexandria and vicinity necessitated development of a well field in the Bayou Rapides area to supplement the supply from wells within the city. The development of this well field, located about six miles northwest of the City, to minimize the pumping interference of existing wells, was preceded by an exploration program designed to permit over-all planning before well construction. The geological and hydrological data obtained were recorded so that future development of ground-water in this area may be properly planned. The testing procedures are outlined in this article to serve as a possible guide for ground-water exploration in other areas.

The exploration program in the Bayou Rapides well field consisted of drilling, electric logging, and testing of six test holes. Samples of the sands and water were collected and analyzed in the laboratory. The water level, temperature, yield, and drawdown were determined for each sand that appeared to have possibilities as an aquifer.

The Bayou Rapides well field is underlain by water-bearing formations of the Miocene, Pleistocene, and Recent series. The Miocene sediments are composed chiefly of alternating sands, sandy shales, and tough clays of fluvial or brackish water origin. The sands are generally fine-grained and very irregular in texture, thickness, and extent. Artesian conditions are present in the sands, recharge taking place in the hills to the north and west where the sands lie at or near the surface.

The principal fresh-water sands of Miocene age range in depth from 150 to 970 feet below the land surface and may be grouped into three well-defined lithologic zones which dip south-southeast at a rate of 75 to 100 feet per mile. Brackish or salt water is found at a minimum depth of 1,100 feet. All of the water in the Miocene sands above this depth is soft and potable.

Alluvial deposits of Pleistocene and Recent age blanket the Miocene sediments. The alluvium underlies Bayou Rapides well field to a depth of 120 feet, grading from clay downward into coarse sand and gravel. The water from the alluvium is hard and not generally considered satisfactory without treatment.

After completion of the testing program in October 1942, six gravel-packed supply wells, 12 inches in diameter and 448 to 998 feet in depth, were constructed by reaming the test holes. The aggregate discharge of the six wells was 2,120 g.p.m. in a pumping test on August 25, 1943, and the individual yields ranged from 260 to 420 g.p.m. The specific capacities of the wells ranged from 1.5 to 8.1. The water is very soft and contains small amounts of fluoride.

The benefits of an adequate exploration program prior to any large development of ground-water are apparent from the results obtained in this project. The definite knowledge of depth, character, and correlation of each water sand, along with the data on quality, temperature, and artesian head of the water therein, permits the careful consideration by the driller and well owner of the most suitable location, depth, construction, and pumping equipment for each well in relation to all other wells.

<sup>1</sup> Published with permission of the Director, Geological Survey, U. S. Dept. of the Interior.

## INTRODUCTION.

GROUND-WATER investigations were begun in Alexandria in 1938 by the Geological Survey, U. S. Department of Interior, in cooperation with the Geological Survey, Louisiana Department of Conservation, at the request of city officials who recognized the impending danger of a water shortage. An areal report on the ground-water resources of Rapides Parish,<sup>2</sup> with a general section devoted to the municipal water supply of Alexandria, was prepared during the winter of 1938-39. At that time the municipal waterworks had ten wells, which were 10 and 12 inches in diameter and from 350 to 1,100 feet deep. These wells were pumped at an average of about 3 million gallons of water daily from sands of the Miocene series. The wells were located in two groups: one near the City Park station at the intersection of Lee Street and Masonic Drive, and the other near the Monroe Street station at 4th and Monroe Streets. The close spacing of these wells caused so much mutual interference that the water levels declined continually. Eventually several wells had to be abandoned and six new wells were drilled at scattered locations within the city. These new wells provided an adequate reserve of water until 1941, when the consumption increased sharply due to the influx of war workers and Army personnel, boosting the population of the city proper from about 28,000 to about 45,000 persons. Additional demands on the water sands were also made by the nearby communities, institutions, and military establishments, resulting in even more serious local overdevelopment of the sands.

Following the suggestions in a previous report,<sup>3</sup> plans were prepared in 1941 to develop a new well field in the Bayou Rapides area as far as practicable from the influence of the existing wells. An irregular tract of land about  $\frac{1}{2}$  mile wide and one mile long located about six miles west of Alexandria (Fig. 1) was purchased by the City of Alexandria for this purpose. A carefully-planned exploratory program was completed in 1942 before any supply wells were drilled. This program is described to encourage adequate testing for ground-water supplies throughout the country. The entire project was sponsored by the Federal Works Agency and resulted in the development of the Bayou Rapides well field.

## EXPLORATORY PROGRAM.

The exploratory program consisted of drilling, electric logging, and testing of six test holes. These were located so that three test holes were along the east side and three along the west side of the field to provide an east-west spacing of about 4,000 feet and a north-south spacing of about 2,500 feet (Fig. 1). Samples of the sands and water contained therein were collected and analyzed in the laboratory. The water level, temperature, yield, and drawdown were determined for each sand that appeared to have possibilities as an aquifer.

<sup>2</sup> Maher, J. C.: Ground-water resources of Rapides Parish, Louisiana. Louisiana Dept. Cons. Geol. Bull. 17, 1940.

<sup>3</sup> Maher, J. C.: Preliminary report on ground-water conditions at Alexandria, Louisiana. Louisiana Dept. Cons. Geol. Pam. No. 2, 1940.

*Method of Test Drilling.*

The test holes, 6 inches in diameter and 1,103 to 1,308 feet deep, were drilled by hydraulic rotary methods in which the drilling is accomplished by rotating a fish-tail bit on the end of a string of drill pipe while mud fluid is pumped down the drill pipe under pressure. The fluid carries the cuttings to the surface and seals the walls of the hole. The hole usually is not cased during the drilling operations, although in some instances surface casing is required to prevent the shallow poorly-consolidated sands from caving into

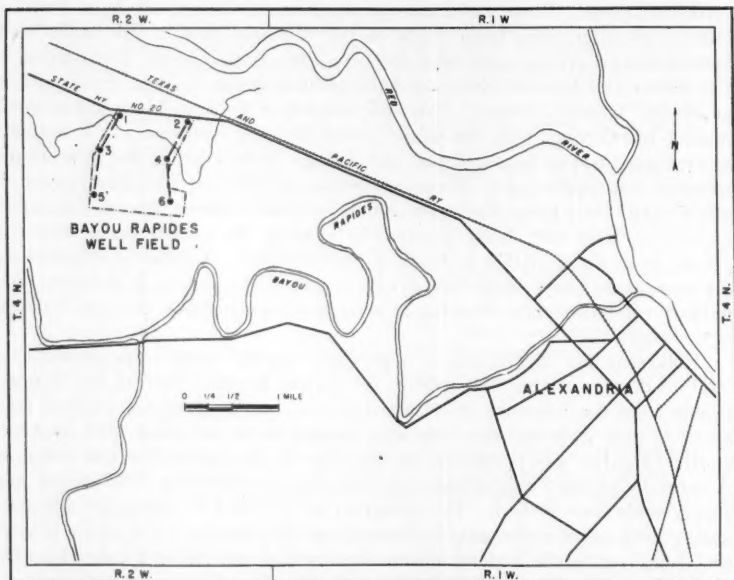


FIG. 1. Map showing locations of wells in Bayou Rapides Well Field, Alexandria, La.

the hole. No surface casing was necessary in the test holes in the Bayou Rapides well field. Both natural mud and Aquagel, a processed commercial drilling mud, were used in drilling these holes. Generally the Aquagel was not used as long as the natural mud was sufficiently viscous to hold up the wall of the hole through the water sands. The test holes were plugged with heavy mud and stiff clay upon completion of the testing.

*Sampling Methods.*

Specifications for the test drilling included a clause providing for the proper collection of samples at ten-foot intervals in each water sand. Whenever a sand was penetrated, the drilling was suspended for 10 to 30 minutes

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(the length of time depending upon the depth of the hole and volume output of the mud pump) while the mud was circulated to clean out the hole. When it was judged that all or most of the drill cuttings had been removed, the ditch returning mud to the pits was cleaned out. Drilling was then resumed until ten feet of sand had been penetrated or the bottom of the sand reached by the bit. Again drilling was stopped and the mud was circulated for 10 to 30 minutes before collecting sample portions at five-foot intervals along the ditch. The combined sample portions were washed free of drilling mud, placed in clean labelled cardboard containers (quart size), and sent to the laboratory for mechanical analysis. The mechanical analyses of these samples were found to be very useful for comparative purposes, even though the rotary method of drilling does not permit accurate sampling of unconsolidated materials.

#### *Drillers' Logs.*

A record of the formations penetrated in each test hole was made by the drillers on the basis of the drill cuttings, the drilling time, the action of the rotary table and mud pump, and the changes in fluid level in the mud pit. The personal equation enters into such records to a considerable degree and the use of such records requires some discretion. It has been found that the logs recorded by an experienced driller, familiar with both the drilling rig and the underground conditions, generally agree fairly well with the electric logs insofar as the principal water sands and hard rock layers are concerned. However, even the best drillers' logs do not show all of the small sand and clay beds which are often lumped together as "sand and shale." In some instances thick water sands have been overlooked by drillers because of some unexpected condition. An example of this occurred in drilling the first test hole in the Bayou Rapides well field when the driller failed to record a thick sand which later proved to have 40 to 60 feet more artesian head than any of the other sands. The driller probably was misled by the fact that the sand was compact and that the artesian head reduced the usual large loss of drilling mud into the sand.

Both drillers' logs and electric logs are desirable in water wells. The drillers' log generally supplies accurate information, permitting the tentative correlation of water sands as the well progresses; the electric log made after completing the hole offers mechanically recorded evidence of the formations penetrated and gives considerable information on the character of the water sands and the water therein.

#### *Electric Logs.*

Upon completion of each test hole, the hole was conditioned by circulating the drilling mud for a period of one to three hours to insure uniformity of mud in all parts of the hole and to build up a heavy mud-cake in the water sands to prevent caving upon withdrawal of the drilling tools. As soon as possible after the removal of the drilling tools, an electric log of the formations penetrated was made by one of the several commercial firms specializing in such services for oil wells.

An electric log is a record of the self-potential and apparent resistivity of the formations penetrated by the drilled hole. The self-potential is recorded as the difference in electric potential between the formations in the hole and a point on the land surface. The apparent resistivity of the formations is determined by sending a current of electricity into the wall of the hole and measuring the rate of potential drop. The equipment used in making these measurements consists of a system of electrodes which are lowered into the hole; a multi-conductor cable spooled on a power-driven winch which raises or lowers the electrodes; a measuring sheave which records the depth of the electrodes; electrical measuring instruments and a source of electromotive force on the land surface connected to the electrodes by the multi-conductor cable; and a plotting mechanism which records measured values of self-potential and resistivity on film.

*Self-potential Curve.* The measured self-potential is shown on the left-hand side of the film or electric log, as a single trace (Figs. 2 and 3), arbitrarily termed "the first curve." In some instances an amplified version of this curve is also shown on the left-hand side of the log, usually as a dashed line. The "first curve" has been generally considered to represent the algebraic sum of potentials generated by *electrofiltration* and *electrochemical action* during and after the drilling of the hole.<sup>4</sup> Recently, however, Lee<sup>5</sup> pointed out the possibility of *natural earth potentials* existing prior to drilling operations. Since any one of these potentials comprising the recorded self-potential may be either positive or negative under different conditions, it is extremely difficult to judge the relative magnitude of each from the "first curve."

The electrofiltration potential is derived from the movement of fluid into or out of the formation due to differences in formational pressure and the weight of the mud column in the hole. When an electrolyte, such as the drilling fluid, is caused to flow through a permeable medium, such as a sand, an electromotive force is set up in the direction of the flow. This electromotive force is proportional to the pressure differential, to the electrical resistivity of the electrolyte, and inversely proportional to its viscosity.

The electrochemical potential is caused by two electrolytes (drilling fluid and formational water) of different ionic concentration being in contact through a permeable medium (sand). The flow of the current is toward the more highly concentrated electrolyte, which may be either the drilling mud or the formational water. It is generally assumed that this potential adds to the electrofiltration potential, but it appears that this would not be true if the more concentrated solution is the drilling mud, as is sometimes the case in water wells.

For many years it was thought that the electrofiltration potential was dominant and, for that reason, the "first curve" was commonly termed the

<sup>4</sup> Deussen, Alexander, and Leonardon, E. G.: Electrical exploration of drill holes. Drilling and Production Practice, Am. Pet. Inst., 1935. Pp. 48, 49.

Gillingham, W. J.: Electrical logging in the Appalachian fields. Penn. State College Min. Ind. Exp. Sta. Bull. 21: 4, 1937.

<sup>5</sup> Lee, F. W.: The possibility of electrical stratification in the earth as disclosed by surface measurements of currents and potentials. Terrestrial Magnetism and Electricity, Trans. Amer. Geophys. Union. 1939. Pp. 383-399.

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"porosity log." Recent studies tend to discredit this idea and to emphasize the complicated nature of the components of the recorded self-potential. In 1942 Dickey<sup>6</sup> made the following statement regarding the relative effect of natural earth potentials on the "first curve":

It has been demonstrated that potential differences exist naturally in the ground at certain points, particularly at geological discontinuities, such as the boundary between a sand and a shale stratum. It is probable that these natural differences of potential are always present, whether or not a well is drilled, and the sandstones are usually negatively charged with respect to the shales.

Little is known of the cause of these natural potentials, and their importance has only recently been recognized. In most published articles on electric logging the potentials have been ascribed entirely to filtration and concentration potentials. . . . Recent work seems to indicate that the natural potentials existing in the ground, regardless of whether or not a well is drilled, are the major source of the potentials measured in electric logging.

**Resistivity Curve.** The apparent resistivity is shown on the right-hand side of the electric log (Figs. 2 and 3) as one, two, or three curves depending

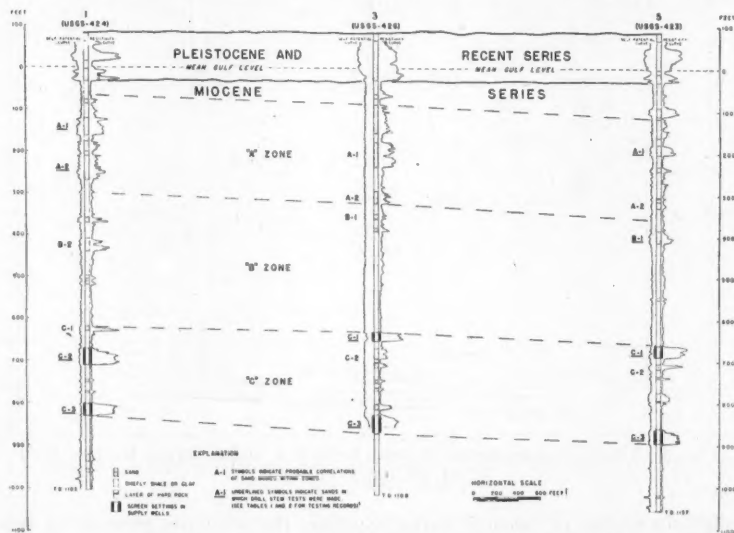


FIG. 2. Geologic cross-section through wells 1, 3, and 5, Bayou Rapides Well Field, as shown on Fig. 1.

upon the number of different electrode spacings used. These curves describe the formations penetrated by the drilled hole in terms of their resistance to the flow of an electric current. Measurable differences in the character of the formations in this respect are primarily dependent not upon the minerals in

<sup>6</sup> Dickey, P. A.: Electrical well logging in the Eastern States. Penn. Topog. and Geol. Surv., Prog. Rept. 129: 8, 9, 1942.







giving the greatest penetration of the formations and, as a result, the most accurate recording of the resistivity of the formations and contained water. A considerable lag in the deflections marking the tops and bottoms of formations is always present in this curve. The "third" and "fourth curves" have been omitted from Figures 2 and 3 for the sake of greater clarity.

*Interpretation.* Since this discussion has been prepared primarily to point out the advantages of electric logs in water wells, no attempt will be made to discuss the more complicated aspects of electric logs and their inter-

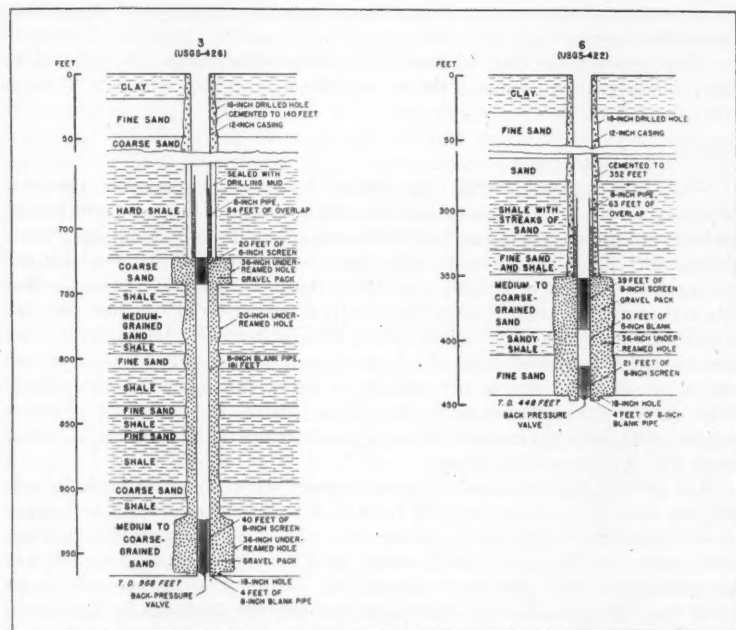


FIG. 4. Diagram showing well construction, Bayou Rapides Well Field, Alexandria, La.

pretation. In general it may be said that an electric log is interpreted by examining the form of the self-potential and resistivity curves with consideration of the resistivity and viscosity of the drilling mud and the temperature range in the hole. There is no handy "rule of thumb" for this interpretation, but the following is generally true in shallow fresh-water wells.

Shales and clays are indicated when both the self-potential and resistivity are low. The almost straight self-potential curve recorded in shale or clay is sometimes referred to as the "shale base"; that is, any deviation from this line indicates a change in the porosity of the formation. This "shale base" may

shift abruptly between marine and continental sediments but remains relatively constant in sediments of any one origin.

Fresh-water sands are indicated by sharp deflections of the resistivity curves to the right, and more moderate deflections of the self-potential curve to either the left or right, away from the "shale base."

Salt-water sands are indicated by no deflection of the resistivity curves or only slight deflection toward the right, and moderate deflection of the self-potential curve to either left or right. Brackish water is often shown by the "third" and "fourth" curves recording less resistivity than the "second" curve because of the presence of less saline mud fluid in the sand adjacent to the drilled hole.

Hard dense rocks are indicated by a sharp deflection to the right of all three resistivity curves and little or no deflection of the self-potential curve from the "shale base."

#### *Drill-stem Tests.*

On the basis of the electric log, drillers' log, and sand samples, the most promising water sands in each test hole were selected for further tests, known by local water-well drillers as "drill-stem tests." The term "drill-stem test," as generally used in petroleum exploration, refers to the use of a patented testing device on the drill stem that allows the fluid in the formation to flow into and partly fill the drill stem under natural pressure. This same patented device can be and has been used in testing some water wells, but is not in common usage by water-well drillers. Instead, many drillers place a short screen section on the drill stem in the sand to be tested and pump the formational water through the drill stem by air. This permits the collection of water samples, and the measurement of water level, temperature, yield, and drawdown with a minimum of delay.

The formational tests in the Bayou Rapides test holes were made by setting ten feet of screen on the drill stem in the selected sand with an improvised canvas or burlap packer above the sand. A commercially-manufactured packer for this type of work would have been more satisfactory but was not available. After placing the screen and packer, a wash line was placed inside the drill stem, and the mud cake opposite the sand was broken down by alternately washing, by forcing water into the well, and pumping the well by air. In order to retain the mud seal on the upper sands, the mud column above the packer was disturbed as little as possible. During the pumping of water from the formation, the level of the mud in the hole outside the drill stem was carefully observed to detect any failure of the packer to hold.

The lowest sand was tested first. The bit was run into the hole and heavy mud was circulated until the sand was sealed. Then the screen was placed opposite the next lowest sand and the process was repeated until all of the selected-sands, usually four in each hole, were tested.

The data obtained from such tests must necessarily be used with discretion. The measurements of yield and drawdown in the test hole give little indication of the probable performance of the final supply well but help somewhat to show the relative water-bearing properties of the different sands.

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Satisfactory water samples, observations of temperatures and static water levels are usually obtained and are worth while.

#### *Results of Exploration.*

The benefits of an adequate test-drilling program prior to any large development of ground-water are apparent from the results obtained in this project. The definite knowledge of the depth, character, and correlation of each water sand along with the data on quality, temperature, and artesian head of the water therein, made it possible to evaluate the possibilities of each sand in each well and the possible interference between wells before any large expenditure of funds was made. The chemical character of the mixture of waters from different sands in the different wells could be estimated to some extent. This was of importance because of the occurrence of fluoride in some of the water. The testing data also allowed careful consideration by the driller and city officials of the most suitable construction method and pumping equipment. Thus few changes or alterations in final plans were needed after construction began. The results obtained in this program indicate that it is generally advisable to conduct the test-drilling program separate from the actual water-supply development in order to allow the preparation of exact specifications which save time, money, and misunderstandings for both the well owner and driller.

#### GEOLOGIC FORMATIONS AND THEIR WATER-BEARING CHARACTERISTICS.

The city of Alexandria is located in the Red River valley, which divides Rapides Parish diagonally from northwest to southeast. In the Kisatchie Hills this valley was cut into the Miocene formations and partially refilled with alluvium by the Red River. About twelve miles north of Alexandria, Bayou Rapides, a relict meander of the Red River, branches off the present Red River channel and follows the base of the southern hills until reaching Alexandria, where it reenters the present channel. The land between this old meander and the present Red River is referred to as "Rapides Island" or more often as the "Bayou Rapides area." The new well field for Alexandria is in this area, about six miles northwest of Alexandria (see Fig. 1). Water-bearing formations of the Miocene, Pleistocene, and Recent series underlie the field.

#### *Miocene Series.*

The Miocene series in Louisiana has been divided by Fisk into two formations, the Catahoula, and the Fleming, which overlies the Catahoula. A controversy over the exact line of demarcation, based upon the calcareous nature of the Fleming formation and the sandy character of the Catahoula formation, has existed for many years. In a recent publication, Fisk<sup>7</sup> classified all of the Miocene sediments above the basal sandstones as Fleming, assigning about 500 feet of predominantly sandy sediments to the Catahoula formation. The entire thickness of Miocene strata was not penetrated by test wells in the Bayou Rapides well field, but the base of the Catahoula formation is reported

<sup>7</sup> Fisk, H. N.: Geology of Avoyelles and Rapides Parishes. Louisiana Dept. Cons. Geol. Bull. 18: 143, 148, 1940.

to have been penetrated at a depth of 1,587 feet<sup>8</sup> in an oil test in sec. 22, T. 4 N., R. 2 W., about one mile north of the well field. This indicates that, if the regional dip is about 75 feet per mile, the base of the Catahoula formation exists at a depth of about 1,650 to 1,700 feet beneath the well field and that the fresh water sands found to a depth of 900 to 1,000 feet may be referred to the Fleming formation as delimited by Fisk.

The sediments of the Miocene series are composed chiefly of alternating loose sands, sandy shales, and tough clays of fluvial and brackish water origin. The sands are generally fine-grained, and very irregular in texture, thickness, and extent. Amorphous silica is present in some of the sands, filling the interstices and reducing the permeability of the aquifers. A few hard sandstones and siltstones, and some bentonitic clays are present in the section. The principal fossil horizon, characterized by the gastropod *Potamides matsoni*, is not present in the part of the Miocene series underlying the well field.

The water sands are separated by thick beds of impermeable shale and clay which confine the movement of the ground-water to a lateral or down-dip direction, resulting in artesian conditions in the Bayou Rapides area. Ground-water recharge is from rainfall where the sands are at or near the surface. Infiltration from surface streams constitutes a very minor part of the replenishment.

The principal fresh-water sands of Miocene age underlying the Bayou Rapides well field range in depth from 150 to 970 feet below the land surface. In test hole 2 a small show of gas was present from 1,034 to 1,038 feet in depth and all of the sands below 1,100 feet contained brackish or salt water. From the electric log of this test hole, the engineers of the electric-logging company estimated that the water in sands at depths of 1,108 to 1,114 feet and 1,270 to 1,302 feet contained 3,300 and 7,800 parts per million of dissolved solids, respectively.

The irregular character of the different sands, typical of Miocene sediments of continental origin, is apparent from the geological cross sections (Figs. 2 and 3). Many of the thicker sands are bifurcate down-dip, and at least one grades completely into shale and clay across the well field. These irregular sand bodies may be conveniently grouped into three well-defined lithologic zones ("A," "B," and "C") for the purpose of local correlation as indicated on the cross sections. The approximate direction and rate of dip of these zones is south-southeast about 75 to 100 feet per mile, which means that the zones become progressively deeper from location 1 to location 6. The probable correlation or interconnection of the sand bodies within the zones is suggested by the symbols, A-1, A-2, etc. on the cross sections. The underlined symbols mark the sands in which drill-stem tests were made (see Tables 1 and 2 for testing records). The final screen settings of the supply wells are also indicated.

#### "A" Zone.

The "A" zone consists of about 240 feet of predominantly sandy sediments between depths of 150 and 390 feet in the northern part of the field and

<sup>8</sup> Idem, p. 194.

TABLE 1.  
RECORDS OF TEST DRILLING IN BAYOU RAPIDES WELL FIELD, ALEXANDRIA.

Test Hole Number. <sup>1</sup>	Completion Date (1942),	Total Depth (feet),	Sands Tested (depth in feet), <sup>2</sup>	Screen Settings (depth in feet),	Static Water Levels in Feet Above (+) or Below (-) Land Surface,	Date of Measurement (1942),	Altitude of Measuring Point (feet), <sup>3</sup>	Yield (g.p.m.), <sup>4</sup>	Temperature (° F.),	Remarks, <sup>5</sup>
1 (USGS-424)	Aug. 27	1103	A-1 (208-249) A-2 (296-355) C-2 (770-810) C-3 (902-932)	222-232 336-346 788-798 913-926	-21.6 -22.0 +25.2	Sept. 4 Sept. 3 Sept. 1 Aug. 29	81.5	3 9 30	73 75	Natural flow 2 g.p.m.
2 (USGS-421)	July 10	1308	C-1 (732-767) C-3 (932-960)	745-755 945-955	-45.3 +25.5	July 11 July 13	77.7	30 25		Natural flow 5 g.p.m.
3 (USGS-426)	Oct. 10	1108	C-1 (723-744) C-3 (920-950)	725-735 937-947	-45.9 +31.3	Oct. 9 Oct. 5	79.3	8 9	73	Natural flow 3 g.p.m.
4 (USGS-425)	Sept. 26	1110	A-2 (367-470) B-2 (552-574) C-1 (758-786) C-2 (831-858)	425-430 565-575 773-783 841-851	-19.5 -9.0 -47.6	Oct. 9 Oct. 8 Oct. 5	80.6	3 20 20 3	74 75	
5 (USGS-423)	Aug. 12	1157	A-1 (272-296) B-1 (480-509) C-1 (759-786) C-3 (960-995)	288-298 480-490 772-782 962-972	-12.8 -47.4 +18.3	Aug. 17 Aug. 16 Aug. 16	82.4	5 20 8	73 76	Natural flow 2 g.p.m.
6 (USGS-422)	July 25	1150	A-1 (330-393) A-2 (449-490)	360-370 482-492	-18.2	Aug. 2	81.2	15 20	72	

<sup>1</sup> See Fig. 1 for locations.<sup>2</sup> See Figs. 2 and 3.<sup>3</sup> Measuring point was land surface at well, and the altitude is in feet above mean gulf level.<sup>4</sup> Yield through drill stem with air.<sup>5</sup> See Tables 2 and 3 for analysis of water samples.

TABLE 2.  
PRELIMINARY EXAMINATION OF WATER SAMPLES FROM TEST WELLS  
IN BAYOU RAPIDES WELL FIELD, ALEXANDRIA.  
Analyzed by E. W. Lohr and J. D. Boreman.

Well No.	Date of Collection.	Depth of Screen (feet).	Bicar-bonate (HCO <sub>3</sub> ).	Sul-phate (SO <sub>4</sub> ). <sup>a</sup>	Chlo-ride (Cl).	Fluo-ride (F).	Ni-trate (NO <sub>3</sub> ).	Iron (Fe).	Total Hard-ness as CaCO <sub>3</sub> .	pH.
(Parts per million except pH)										
1 USGS-424	9/ 9/42	222-232	577	5	36	2.0		0.62	82	8.0
	9/ 3/42	336-346	648	1	37	2.4			20	8.3
	9/ 2/42	788-798	266	1	15	1.5			10	8.3
	8/29/42	916-926	238	1	9	1.0			10	7.7
2 USGS-421	7/ 1/42	100-110	614	70	26		4.2		465	
	6/27/42	757-767	310	1	18		.8		14	
	7/13/42	945-955	318	2	15			1.28 <sup>b</sup>	14	7.3
3 USGS-426	9/28/42	105-115	668		16			3.5	510	7.3
	10/ 5/42	725-735	320	2	13	1.5			15	8.4
	10/ 5/42	937-947	290	1	11	1.2		0.24 <sup>b</sup>	18	8.3
4 USGS-425	10/ 9/42	423-430	666	8	52	1.9			36	8.4
	10/ 8/42	565-575	404	2	16	1.4			21	8.1
	10/ 6/42	773-783	312	6	16	1.5			21	8.0
	10/ 5/42	841-851	348	8	17	1.4		0.99	18	7.9
5 USGS-423	8/13/42	106-116	606	110	63	0.2			315	
	8/18/42	288-298	632	15	30	2.2			39	
	8/17/42	480-490	660	2	27	1.7		c	15	
	8/17/42	772-782	280	3	15	1.3		c	12	
	8/15/42	962-972	366	3	15	1.4		c	36	
6 USGS-422	8/ 1/42	88- 98	634	65	16	0.4			510	
	8/ 1/42	360-370	658	4	34	2.1			21	
	7/30/42	482-492	656	1	37	2.5		c	21	

<sup>a</sup> By turbidity, approximate.

<sup>b</sup> Iron soln. 0.24, pptd. 1.04, approximate.

<sup>c</sup> Iron low. Probably less than 0.1 p.p.m.

<sup>d</sup> Sulphate low.

between 240 and 480 feet in the southern part. From three to six irregular sand bodies were logged in this zone in each test hole; however, only two sands were coarse and thick enough for consideration as water sands. These are designated as A-1 and A-2 on the cross sections.

*A-1 Sand.* The top of the A-1 sand ranges from 207 feet below the surface at location 1 on the up-dip side of the field to 330 feet in well 6 on the down-dip side. This sand is extremely irregular in thickness and grain size. Its maximum thickness is 63 feet in well 6; its minimum thickness is 21 feet in well 4. Mechanical analyses show that this sand is very fine-grained at locations 1 and 2, medium- to coarse-grained at locations 4 and 5, and rather coarse-grained (80-90 per cent of grains exceed 1/4 mm. in size) at locations 3 and 6.

Drill-stem tests were made in this sand at locations 1, 5, and 6 where the sand appeared to be most promising for development. The static water level



observed in those tests ranged from 18 to 21 feet below the land surface (see Table 1). Yields of 3 to 15 gallons a minute were obtained by pumping with air. As mentioned in the section on "Drill-stem tests," the yields of sands in such tests are valuable only in comparison with results of similar tests in other sands. Thus the yield of 15 gallons a minute at location 6 is considered relatively large and this sand was later developed along with the A-2 sand in supply well 6.

The water from the A-1 sand has a temperature of 72° F. and a hardness ranging from 21 to 82 parts per million. The hardness of this water is considerably more than that of water from the deeper sands, where natural softening, occurring in most Miocene sands, has more nearly reached completion. The fluoride content of the water is almost uniform at 2 to 2.2 parts per million.

*A-2 Sand.* The A-2 sand, near the base of the "A" zone, ranges from 20 feet (location 5) to 103 feet (location 4) in thickness. The top of the sand is found at a depth of 265 feet at location 1, and at a depth of 449 feet at location 6. It is fine-grained in character at all locations except nos. 4 and 6 where it was later developed in supply wells.

This sand was tested at locations 1, 4, and 6. Observed static water levels ranged from 19.5 to 21.5 feet below the land surface. Relatively small yields, 3 to 9 gallons a minute, were obtained in the tests. The water has a temperature of 73 to 74° F., a hardness of 20 to 36 parts per million, and a fluoride content of 1.9 to 2.5 parts per million.

#### "B" Zone.

Immediately below the sandy sediments of the "A" zone in the Bayou Rapides well field there are about 300 feet of clay and shale containing only two or three fine sands. This zone, designated "B," ranges in depth from 385 to 715 feet in the northern part of the field to 490 to 809 feet in the southern part. Two of the sands, B-1 and B-2, were tested at locations 4 and 5 but were not developed in any of the supply wells.

*B-1 Sand.* This sand is extremely irregular in character, being entirely absent at location 4. At all other locations except no. 5, it contains considerable clay and shale. At location 5 the sand is 29 feet thick, the maximum recorded in the field, and rather coarse-grained. A drill-stem test at this location showed a static water level of 12.8 feet below the land surface and a rather large yield of 29 gallons a minute. The water has a temperature of 73 to 74° F., a hardness of 15 parts per million, and a fluoride content of 1.7 parts per million.

*B-2 Sand.* Like the B-1 sand, this sand is fine-grained and very irregular in thickness. It is absent at locations 3 and 5, and even at location 4, where it is best developed, it contains several clay layers. A yield of 20 gallons a minute was obtained in the test at location 4. The static level was 9 feet below the land surface. The quality of the water from this sand is very similar to that of the B-1 sand, having a hardness of 21 parts per million and a fluoride content of 1.4 parts per million.



### "C" Zone.

This zone consists of about 225 to 235 feet of predominantly sandy sediments ranging in depth from 715 to 970 feet in the northern part of the well field and from 760 to 995 feet in the southern part. There are three principal water sands in this zone.

*C-1 Sand.* The C-1 sand is best developed at location 2 where it is 62 feet thick, and rather coarse-grained, though poorly sorted. This sand is one of the most important water sands and was tested in all test holes except test hole 6. The yields on the tests ranged from 8 to 30 gallons a minute with most of the yields over 20 gallons a minute. The water levels ranged from 45 to 47 feet below the land surface. Screens were set in this sand in supply wells 2, 3, and 5. The water is very soft (10 to 21 parts per million of hardness) and has a lower bicarbonate content than the water from the upper sands. The fluoride content is 1.3 to 1.5 parts per million. The temperature is about 75° F.

*C-2 Sand.* This sand, which probably represents a bifurcation of the C-1 sand farther north, is thin and fine-grained at all locations except location 1 where it is 40 feet thick and coarse-grained. The yields of drill-stem tests in this sand in test holes 1 and 4 were 30 and 20 gallons a minute respectively. The static water level was about 47 feet below the land surface. This sand is screened in only one supply well, No. 1. The water is very soft and has a fluoride content of about 1.5 parts per million.

*C-3 Sand.* The C-3 sand is one of the principal water sands in the well field despite the fact that it grades into clay and shale at location 6 (Fig. 3). It is medium- to coarse-grained and has sufficient pressure to flow at the surface. Drill-stem tests were made in this sand at locations 1, 2, 3, and 5, and later screens in supply wells were set in this sand at the same locations. The natural flow from this sand was 2 to 25 gallons a minute during the drill-stem tests. The artesian head or the height to which the water would rise in wells penetrating this sand ranged from 18.3 feet above the land surface at location 5 to 31.3 feet at location 3. The water is very soft (10 to 36 parts per million) and contains 1.0 to 1.4 parts per million of fluoride.

### *Pleistocene and Recent Series.*

Sand, gravel, and clay of Pleistocene and Recent age blanket the Miocene formations in this area. The Pleistocene deposits have been described by Fisk<sup>9</sup> as four formations (Prairie, Montgomery, Bentley, and Williana) which form four terraces above the present Red River flood plain. The flood plain, on which the Bayou Rapides well field is situated, is underlain by about 120 feet of Recent deposits of alluvium grading from clay downward into coarse sand and gravel. The upper or surficial clay is about 20 feet thick throughout the area. The sand below this clay is very irregular with some clay streaks at depths of 40 to 60 feet. The coarse material generally is found below a depth of 65 feet. Gravel is not present at all locations,

<sup>9</sup> Fisk, H. N.: *Geology of Avoyelles and Rapides Parishes.* Louisiana Dept. Cons. Bull. 18: 175, 1940.

although the sand is generally coarse enough to yield moderate supplies of water.

Drill-stem tests of the Recent alluvium were not made in the test holes, as four small-diameter wells drilled into the alluvium at locations 2, 3, 5, and 6 to obtain drilling water supplied the needed samples and data. The water level in these wells was about 5 feet below the land surface. The 4-inch well at location 2 yielded 80 to 90 gallons a minute pumping with air. (This yield should not be compared to yields of deeper sands which were pumped through 2½-inch drill pipe.) The temperature of the water is about 65 to 67° F. All of the water is hard (see Table 2). The hardness ranges from 315 to 510 parts per million. Considerable amounts of iron are present in this water, making it unsuitable for most domestic purposes without treatment.

#### SUPPLY WELLS.

##### *Construction of Wells.*

After completion of the test drilling in October 1942, six gravel-packed supply wells, ranging from 448 to 998 feet in depth, were constructed by reaming the original test holes to a diameter of 18 inches to the desired depths. Casing, 12 inches in diameter, was set to depths of 350 to 768 feet in the wells. The selected water sands were underreamed to a diameter of 36 inches. Screens, 8 inches in diameter and 20 to 72 feet long, were placed in the underreamed sections (Fig. 4). Screens were set in the C-1 and C-3 sands in wells 2, 3, and 5; in the C-2 and C-3 sands in well 1; in the A-1 and A-2 sands in well 6, and in the A-2 sand in well 4. Graded pea-gravel was packed around the screens by means of inductor pipes. In all wells, the outside casing was cemented in the hole to protect the well against contamination. Deep-well turbine pumps, capable of pumping 250 gallons a minute against a head of 250 feet, were installed in all wells with the bowls set 250 feet below the pump base. Water-level observation equipment, consisting of an altitude gage connected to a ¼-in air line extending to the pump bowls, was placed on each well.

##### *Yield of Wells.*

The combined yield of the six wells was 2,120 gallons a minute, or 3,058,560 gallons a day when measured on August 25, 1943. The yields of the individual wells, measured while other wells were being pumped, ranged from 260 g.p.m. (well 5) to 420 g.p.m. (wells 1 and 2). The low yield of well 5, screened in the C-1 and C-3 sands, is not necessarily indicative of low permeability of the sands at this location, as it may be the result of less successful gravel-packing or under-development of the sands, which can be overcome by reworking. When completed, wells 1, 2, and 3, screened in the C-3 and the C-1 or C-2 sands, flowed 65 to 72 g.p.m. at the surface despite the partial loss of head caused by the flow of water from the C-3 sand (artesian head, 18 to 31 feet above surface) into the C-1 and C-2 sands (water level, 45 to 47 feet below surface). The differences in head of these sands, as measured in the test holes, amounts to 65 to 78 feet.

The specific capacities of the wells, i.e., the yields per foot of drawdown, range from less than 1.5 g.p.m. to more than 8 g.p.m. Wells 1 and 2, completed in the "C" zone, have specific capacities of about 8 g.p.m., but wells 3 and 5, also completed in the "C" zone, have specific capacities of only 2.4 and 1.5 g.p.m. respectively. Both wells 4 and 6, screened in the "A" zone, have specific capacities of 4.4 g.p.m. although well 6 is screened in the A-1 and A-2 sands and well 4 is screened only in the A-2 sand.

The only well which has been pumped for a long period is well 6, which is used to supply the nearby air base. It has yielded an average of 300,000 gallons a day since October 1942, when it was completed. Its yield was 340 g.p.m. on August 25, 1943.

The purpose in constructing this new well field outside the city limits was to avoid the serious interference of the numerous municipal, industrial and institutional wells in and north of Alexandria. Wide spacing and the limitation of pumpage to 200 to 250 g.p.m. per well were proposed to minimize mutual interference within the well field. At the time that the wells were tested in August 1943, the yields of most of the wells were considerably in excess of that figure, and one new large-diameter well had already been drilled on adjacent property. Since the pumpage from this field is not intended to supplant that from the old city wells but rather to supplement it in such a way that the less efficient wells in the city may be abandoned, it is deemed advisable to reduce the pumping to meet the original requirement of 200 to 250 g.p.m. per well.

#### *Quality of Water.*

The procedure followed in the exploratory program preceding the construction of the supply wells included the sampling of water from all prospective water sands in the test holes. These samples were sent to the Water Resources Laboratory, Washington, D. C., for preliminary examination. The results, shown in Table 2 and discussed in connection with the geology, were used in the selection of the sands for development in the supply wells. Complete chemical analyses of the water from the supply wells were also made and are shown in Table 3. Due to the completion of five wells with two screens each, these analyses represent the chemical character of a mixture that may change slightly in chemical composition with variation in yield of the two sands screened in any one well.

Referring to Table 3, it is evident that the water from the deeper wells (wells 1, 2, 3, and 5) in the "C" zone is somewhat better than that from the shallower wells (wells 4 and 6) in the "A" zone. The hardness of the water is about the same in the two zones (3.6 to 10 parts per million compared to 14 to 16 parts per million), but there is considerable difference in the amount of bicarbonate, chloride, fluoride, and dissolved solids. The bicarbonate content of the water from the deeper wells ranges from 245 to 313 parts per million as compared to 656 to 678 parts per million in the water from the shallower wells, causing most of the difference in total dissolved solids. The small difference in chloride content is not important, but the lesser amount of fluoride, 1.0 to 1.2 parts per million, in the water from the "C" zone is more

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Sodium  
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Bicarbon  
Sulphate  
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TABLE 3.  
ANALYSES OF WATER SAMPLES FROM SUPPLY WELLS IN BAYOU RAPIDES  
WELL FIELD, ALEXANDRIA.

Analyzed by E. W. Lohr. Samples collected August 25, 1943.

Well Number.....	1 USGS 424	2 USGS 421	3 USGS 426	4 USGS 425	5 USGS 423	6 USGS 422
Depth (feet).....	934	966	968	466	998	448
	(Parts per million except pH)					
Silica (SiO <sub>2</sub> ).....	44	44	46	36	47	42
Iron (Fe).....	.24	.01	.04	.04	.03	.03
Calcium (Ca).....	.6	2.2	1.0	4.9	1.2	4.0
Magnesium (Mg).....	.5	1.1	.4	.9	.4	.8
Sodium (Na) and potassium (K).....	99	124	106	283	121	268
Bicarbonate (HCO <sub>3</sub> ).....	245	313	262	678	297	656
Sulphate (SO <sub>4</sub> ).....	1.2	1.4	1.3	.9	1.0	1.0
Chloride (Cl).....	10	13	11	48	14	36
Fluoride (F).....	1.0	1.2	1.1	2.1	1.2	2.2
Nitrate (NO <sub>3</sub> ).....	.0	.0	.0	.0	.0	.0
Total dissolved solids.....	268	319	295	712	335	680
Total hardness as CaCO <sub>3</sub> .....	3.6	10	4.2	16	4.5	14
pH.....	7.7	7.8	7.6	7.8	7.5	7.9

desirable than the 2.1 to 2.2 parts per million in the "A" zone water. The presence of more than 1 part per million of fluoride in drinking water may cause mottled enamel,<sup>10</sup> a disfiguring dental defect of children's teeth, but recent studies have shown that small amounts inhibit decay. According to Dean:<sup>11</sup>

It has been shown epidemiologically that school children using domestic water containing as little as about one part per million of fluoride experience only one half to a third as much dental decay as comparable groups using fluoride-free water such as Lake Michigan or the Mississippi River waters. . . .

Apparently teeth require traces of fluoride for optimum dental health, although excessive amounts may result in the disfiguring condition known as mottled enamel. The difference between 0.0 and 1.0 part per million of fluoride (F) in the domestic water supply has been shown to be highly significant from the standpoint of the amount of dental decay in a community.

At present the total supply from well 6 and part of that from well 4, both of which yield water containing 2.1 to 2.2 parts per million of fluoride, is being used at the air base. If this is ever pumped into the city mains, it may cause the fluoride content of the mixture to increase slightly. If necessary, the water from the Bayou Rapides well field can be mixed with water from the old wells in the city which contains less than 1 part per million of fluoride.

#### *Additional Water Supply.*

The ground-water resources of this area, like other resources, are limited and can be overdeveloped unless the pumpage is properly regulated and the well distribution is carefully planned. If it becomes necessary for the city of

<sup>10</sup> Dean, H. T.: Chronic endemic dental fluorosis. Jour. Am. Med. Assoc. 107: 1269-1272, 1936.

<sup>11</sup> Dean, H. T.: Fluorine and dental health. A. A. A. S. Bull. 1: 47, August 1942.

Alexandria to drill additional wells, it is suggested that test holes, 1,100 feet deep, be drilled at one mile intervals along the pipe line toward Alexandria and along the highway toward Boyce. The findings of these test holes will determine the depth and number of wells needed.

Conservation of the deep soft water in the Alexandria area should be encouraged. The large quantities of hard water available from the alluvium in the Red River valley have not been developed to any extent. This water would require softening and removal of iron before it would be satisfactory for general municipal use (see Table 2), but it could be used without treatment for air conditioning or industrial cooling purposes. The advantages of using this water for such purposes are the low temperature ( $67^{\circ}$  F.), the large quantities available without endangering public supplies, the low cost of shallow wells, and the relatively high water level.

DIVISION OF GROUND WATER,  
U. S. GEOLOGICAL SURVEY,  
WASHINGTON, D. C.,  
*March 8, 1944.*

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# GEOLOGIC FACTORS AFFECTING THE PERENNIAL YIELD OF ARTESIAN AQUIFERS IN THREE AREAS IN MISSISSIPPI.<sup>1</sup>

GLEN F. BROWN.

## ABSTRACT.

Pumping tests furnished data for calculation of coefficients of storage and transmissibility at three army camps in Mississippi but water-level declines depend also on correct analysis of the geology of Tertiary sediments involved.

The water supply for Camp McCain comes from an upper sand of basal Claiborne age and a lower sand of middle Wilcox age. The productive basal sand of Claiborne age has a large catchment area in its nearby outcrop, where it overlaps the sand of middle Wilcox age. The lower of these two sands is a nearly discontinuous deposit in three east-west tortuous ancient channels truncated near the middle of the camp by a north-south reverse fault. The cones of depression in it are extensive and irregular and the coefficients of transmissibility and storage range widely. It yields less water than the upper sand but its water is of better quality, and has therefore been developed to economic maximum.

The Camp Van Dorn water supply comes from four aquifers within a Miocene deltaic mass. Most wells are in a sand at the base of the Homochitto member of the Pascagoula formation, which crops out 15 miles up-gradient and north of the camp. Large undeveloped supplies remain.

The water levels at Camp Shelby declined for six months and then remained nearly stationary for more than a year. No outcrops of the water-bearing sand of Miocene age could be found, but recharge occurs from the Pleistocene gravels in nearby river valleys.

This paper is based on ground-water investigations made in cooperation with the Mississippi State Geological Survey.

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<sup>1</sup> Published with the permission of the Director of the Geological Survey, United States Department of Interior, and the Director of the Mississippi State Geological Survey.  
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## INTRODUCTION.

THE water supplies for Camps Van Dorn and McCain, Mississippi (Fig. 1) and one-fifth of the supply for Camp Shelby, Mississippi, have been developed since Pearl Harbor. The water supplies for the three camps come from wells which penetrate water-bearing sands in unconsolidated Tertiary sediments. At Camp Van Dorn nine wells were drilled and equipped to pump from 245 to 940 gallons per minute; at Camp McCain 15 wells were drilled and equipped to pump from 133 to 400 gallons per minute; at Camp Shelby 15 wells were drilled and equipped to pump from 333 to 900 gallons per minute. The Federal Geological Survey made pumping tests in cooperation with the



FIG. 1. Location of areas described in this paper.

Area Engineers, U. S. Engineers, and architect engineers at Camps McCain and Van Dorn before the camps were populated. A series of tests was made at Camp Shelby in cooperation with the Area and Post Engineers, U. S. Engineers, after most of the wells had been in operation over a year. The tests were made to ascertain, if possible, the safe yields of the sands by determining the coefficients of transmissibility (number of gallons of water a day that will move through a mile wide vertical strip the height of the aquifer and having a hydraulic gradient of one foot per mile normal to the strip) and the coefficients of storage (cubic feet of water released from storage in a column of the aquifer having a base of one square foot when the piezometric surface is lowered one foot). Where these coefficients can be accurately determined and their changes can be evaluated in the area influenced by

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pumping, the methods developed by Theis<sup>2</sup> permit accurate prediction of water-level decline resulting from pumping. This paper evaluates the geologic conditions that influence such predictions in the areas investigated.

The Army camps are on the Gulf Coastal Plain where sediments dip to the south as part of the northern flank of the Gulf Coastal geosyncline. The Mississippi embayment is an auxiliary trough, whose axis trends roughly perpendicular to the axis of the geosyncline and approximately parallel to the course of the Mississippi River. Thus the Tertiary sedimentary units involved swing across Mississippi from a west strike near Camps Van Dorn and Shelby, in the southern part of the state, and a north strike near Camp McCain, in the northwestern part of the state. In general, the catchment or recharge areas for the ground-water supplies at Camps Van Dorn and Shelby are north of the camps; at Camp McCain the recharge area is east of the camp.

#### CAMP MCCAIN.

The ground-water supplies at Camp McCain, nearby towns, and the Grenada Air Base come from two water-bearing sands—the basal Meridian sand member of the Tallahatta formation, the lowest formation of the Claiborne group of middle Eocene age, and a deeper sand which is stratigraphically near the middle of the non-marine Wilcox group of lower Eocene age. The Meridian sand was found in borings from the surface of the land to a depth of 280 feet and the sand of Wilcox age was found at depths from 284 to 521 feet.

*Geology of the Meridian sand member of the Tallahatta formation.* The Meridian sand member of the Tallahatta formation unconformably overlies the sediments of Wilcox age and conformably underlies the Basic City shale member of the Tallahatta. The interbedded relationship of the Basic City shale and the Meridian sand does not permit a clean-cut separation of these two members, for lenses of shale similar to the Basic City shale are scattered through the Meridian sand member, and sand lenses similar to the Meridian sand appear in the overlying Basic City shale. Coarse sand is most abundant in the lower middle portion of the sand member. A few grains exceed 1 mm. in diameter, and in local outcrop areas fine gravel is exposed, but beneath the camp the basal portion is fine-grained. Probably the most characteristic feature of the sand is the large amount of muscovite, coarser kyanite, and staurolite, all easily seen with a hand lens. The Meridian sand can be followed across the state. In the northwestern part it covers a wide area formerly assigned to the Holly Springs terrain.<sup>3</sup> It extends down dip beneath the Mississippi alluvial plain where the sand thickens to form the most important source of artesian water in the Yazoo "delta."

<sup>2</sup> Theis, C. V.: The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Am. Geophys. Union Trans.*, pp. 519-524, 1935.

Theis, C. V.: The significance and nature of the cone of depression in ground-water bodies. *ECON. GEOL.* 33: 889-902, 1938.

<sup>3</sup> Stephenson, L. W., Logan, W. N., and Waring, G. A.: Ground-water resources of Mississippi. U. S. Geol. Survey Water-Supply Paper 576: Plate 2, 1928.



from the southeast toward the northwest prior to camp pumping. After a year's intermittent pumping of nine wells in this sand, the water levels have not declined appreciably. In the southeastern part of the cantonment area and in an area northwest and on the upthrown side of the fault the water is under water-table or semi-confined conditions. Although only the lower part of the valley of the east fork of Batupan Bogue is underlain by the Meridian sand, water from the 100 square mile drainage area of the east fork is available for recharge. The limiting factor for total water available to the wells in the Meridian sand is the effectiveness of the hydrologic connection along the channel of the east fork (where there is much silt and clay) and the effectiveness of the connection with the alluvium and colluvium which cover the valley floor and the subjacent Meridian sand. The water in the Meridian sand is of good chemical quality except that dissolved iron and carbon dioxide are present in undesirable quantities. An attempt was made to treat the water with sodium meta-phosphate (trade name, "calgon") to prevent precipitation of iron, but mechanical difficulties hindered a completely satisfactory treatment. However, two wells that penetrate the sand in the structurally low area east of the fault contain less iron than the others, and are used to furnish water during peak demand to supplement the remainder of the supply which is derived from the deeper sand of Wilcox age.

*Geology of the Wilcox sand member.* The basal sand bed near the middle of the Wilcox group is a nearly discontinuous sand horizon composed of three east-west sinuous channelways which are sealed across the center of the camp by a fault (Fig. 3). On the west side of the fault most of the sand is near the southern cantonment boundary, the lenses or fingers of sand thinning to the northwest from 123 feet to 11 feet for individual beds, in a distance of 3 miles. On the east side of the fault the thickness ranges from less than 10 feet to about 100 feet.

The sand is fine-grained, and locally contains many micaceous grains. Generally the lower few feet are composed of gray angular quartz sand. It is typical of the non-marine Wilcox deposits, containing much carbonaceous shale and silt, lignite, and discontinuous lenses and pockets of fine sand. Thin layers of carbonate-cemented siltstone and sandstone with a few glauconite grains are scattered through it and are useful to the geologist for local correlation. The outcrop area appears to be silty sand exposed in lenses less than one-half mile in width and about 15 miles east of the camp.

*Hydrology of the sand of Wilcox age.* The quality of water from the sand of Wilcox age is good and does not require treatment. Accordingly, an attempt was made to develop it to the limit of safe yield, a problem made difficult by the heterogeneity and structure of the aquifer. The recharge area was considered to be 15 miles east of the camp and the piezometric surface showed a general southwest to northwest movement. Short-term pumping tests gave coefficients of transmissibility ranging from 1,500 to 19,925 and coefficients of storage ranging from 0.00015 to 0.00080. The geologic evidence indicated that an average of these figures could not be used to predict drawdowns, so each well was studied separately. It was found that in four wells east of the fault pumping any one well caused water-level decline in the

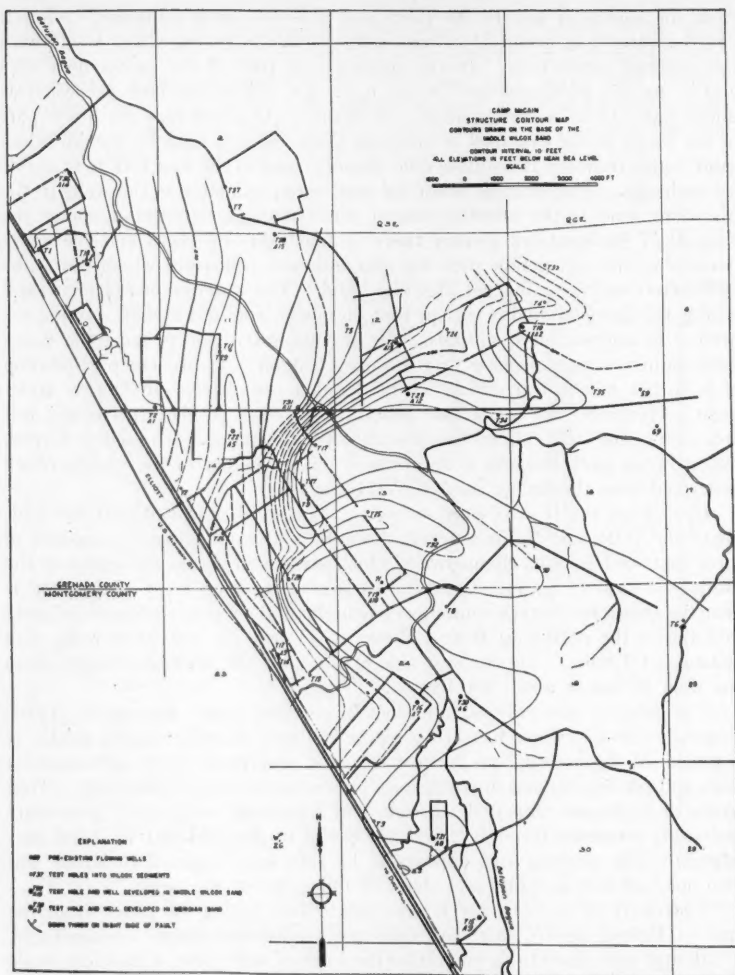


FIG. 3. Structure contour map of the base of the sand of Wilcox age at Camp McCain.

others but had no apparent influence on water levels in two wells behind the fault (away from recharge).

After pumping for one year, the decline of water levels was compared with predicted declines. Although the predicted declines were not greatly in error, it was apparent that transmissibility was much less than that shown

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in the pumping tests and accordingly storage was greater. The recharge necessary for steady state behind the fault would require that the water move around the ends of the fault or that a sufficient volume of sand be present to supply the two wells from storage during the life of the camp. The declines of water levels behind the fault are comparable to the declines on the recharge side, suggesting that possibly water can move around the ends of the fault or a large storage reserve exists west of the camp.

#### CAMP VAN DORN.

*Geology and development.* Camp Van Dorn lies in an area where no large ground-water developments had been attempted prior to camp construction. Accordingly, it was desirable that all the fresh water beds be explored and the most favorable chosen for development. Nine wells were drilled, six of which ranged in depth from 409 feet to 476 feet and were developed in the basal sand of the Homochitto member of the Pascagoula formation (Miocene). The remaining three wells were each developed in separate sands, the lowest, completed at a depth of 1,699 feet, probably being in the Catahoula sandstone, a second well, 902 feet deep, being in a sand believed to be at the base of the Pascagoula formation, and a third, 222.5 feet deep, in the basal sand of the Fort Adams member of the Pascagoula formation. The aquifers are within a Miocene deltaic mass and the tentative correlations are based on lithology, mineralogy, dip from outcrops exposed north and northwest of the camp, and the chemical composition of the waters. They are by no means certain. The outcrops area of the aquifers may be found a few miles north of the camp where the Fort Adams member of the Pascagoula formation is exposed to about 90 miles north of the camp where the Catahoula sandstone is exposed.

All of the aquifers are of continental or estuarine origin. Aquifer grain sizes range from fine sand to very coarse sand and fine gravel. The coarser sands penetrated by the wells are in the Catahoula sandstone, the basal sand of the Pascagoula formation, and the basal sand of the Homochitto member of the Pascagoula formation.

*Hydrology.* Of the four water-bearing sands furnishing water to Camp Van Dorn, most of the water comes from the basal sands of the Homochitto member of the Pascagoula formation. The coefficients of transmissibility, as determined by pumping tests, range from 32,800 to 174,000 and average about 45,000. Storage ranges from 0.00027 to 0.00057 and averages 0.0004. As the only single wells are developed in the other three sands, only coefficients of transmissibility could be determined by Theis' recovery method. A coefficient of 440,000 was obtained for the Catahoula sandstone during the first 1½ hours of recovery following pumping and 1,032,000 for the next 14 hours. The recovery of water levels following pumping of two test periods indicated a coefficient of transmissibility of 99,000 and 76,000 for the sand at the base of the Pascagoula formation. The rate of recovery suggested a coefficient of 3,900 for the sand in the lower part of the Fort Adams member of the Pascagoula formation.

The tests indicate that large ground-water supplies are available at Camp Van Dorn, and only relative depths to water in the aquifers beneath the Fort Adams member and the quality need be considered when planning future supplies. All the waters are low in total dissolved solids. The water in the Fort Adams and Homochitto members of the Pascagoula and the Catahoula sandstone contain appreciable amounts of iron and free carbon dioxide, requiring some treatment. The water from the basal sand of the Pascagoula formation is satisfactory for most uses without treatment.

#### CAMP SHELBY.

*Geology and development.* Camp Shelby is underlain by the eastern extension of the same deltaic or estuarine beds which supply fresh water to Camp Van Dorn. The fresh water is contained in the coarse non-marine clastics of the Catahoula sandstone above the *Heterostegina* limestone zone. This zone in the Catahoula marks the bottom of fresh water in a large area in southern Mississippi. Hattiesburg, 7 miles north of the camp, derives water from the Catahoula sandstone, and in 1918 some wells were drilled to it at Camp Shelby. However, adequate supplies have been found in sand lenses intercalated in clays of the overlying Hattiesburg formation (Fig. 4). All screens of wells at the camp are set in the lower of two extensive sand lenses whose longest horizontal diameters are east-west. They tend to wedge out up-dip and north of the camp. The lower sand bed averages about 90 feet in thickness beneath the camp; the upper sand is thinner and more irregularly distributed. Both sands grade vertically into silt and clay and appear to be connected up-dip to Pleistocene stream gravels that extend 80 feet below part of the Leaf River Valley north of the camp.

*Hydrology of the Hattiesburg formation.* Pumpage at Camp Shelby caused water levels to decline until March 1942. Periodic measurements made until July 1943 when an observation well was installed in the center of the camp well field showed that the water levels fluctuated with pumping but no longer trended downward. The fluctuations in the observation well from July to the end of 1943 show that general steady state has been reached at the present rate of pumpage. Pumping tests indicated that the coefficient of transmissibility ranged from 32,300 to 133,000 and that the coefficient of storage ranged from 0.00018 to 0.00046. Average transmissibility was near 67,000 and average storage was near 0.00031. These coefficients give a decline of water levels somewhat greater than was measured.

A well  $3\frac{1}{2}$  miles east of the camp yields water from the lower sand. The water level in that well was 12 to 22 feet lower than the highest levels reached in wells at the camp during the period May 20 to June 15, 1943. A well about one mile east of the camp is set in the upper sand, yet the water level fluctuates violently with camp pumpage. A pressure surface map based on highest water-level measurements during May 20 to June 15, 1943, shows an area of high pressure extending south from the Grenada Air Base and in the direction of the camp. This evidence is interpreted to mean that the two sands are hydrologically connected and are connected to the Pleistocene gravel



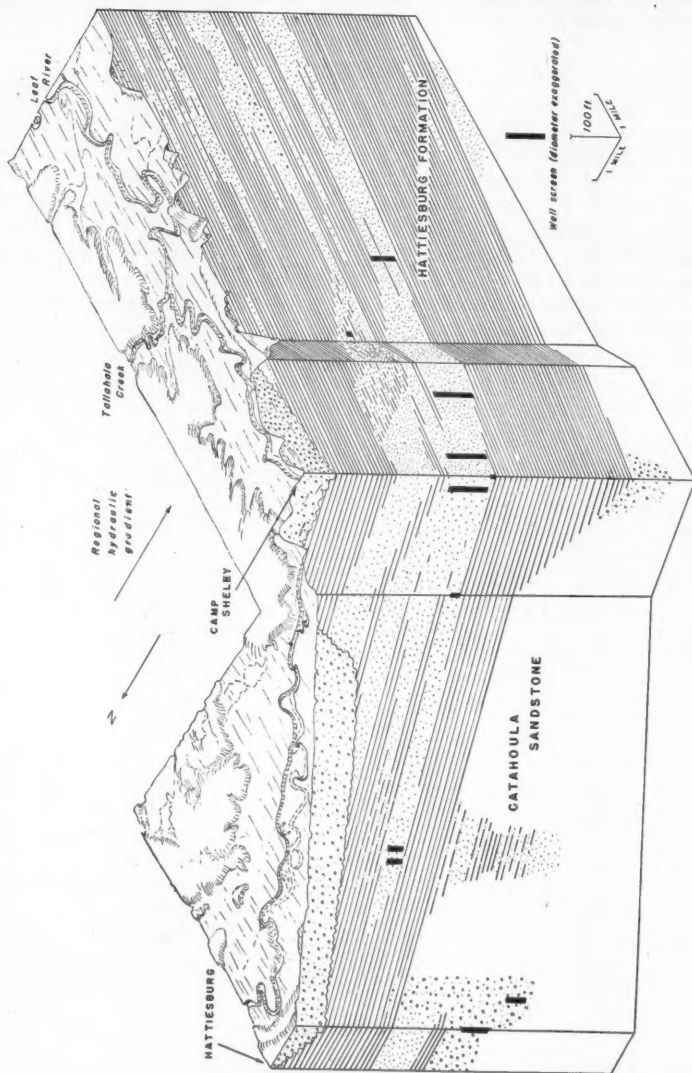


FIG. 4. Isometric block diagram of part of the Camp Shelby area.



beneath the Leaf River north of the camp. Recharge from the gravels will probably prevent any extensive decline in water levels at the camp.

#### ACKNOWLEDGMENTS.

The results given in this paper represent effort by several colleagues, but the writer is solely responsible for the interpretations. Major Arthur P. Banta, U. S. Engineers, and V. T. Stringfield, U. S. Geological Survey, have encouraged the work and discussed various phase with the writer. R. W. Adams and W. F. Guyton did much of the field work and calculations of results from pumping tests. Prof. Calvin S. Brown, University of Mississippi, kindly read and criticized this paper. The investigations were made in cooperation with the U. S. Engineers and the Mississippi Geological Survey. More detailed descriptions of the investigations at Camps McCain, Van Dorn and Shelby are contained in bulletins 55, 56 and 58 of the Mississippi State Geological Survey.

# QUANTITATIVE STUDIES OF SOME ARTESIAN AQUIFERS IN TEXAS.<sup>1</sup>

W. F. GUYTON AND N. A. ROSE.

## ABSTRACT.

Large quantities of ground water have been pumped for many years in Texas from formations of Cretaceous, Eocene, Miocene, Pliocene, and Pleistocene age. Declines in water levels have resulted and investigations have been made by the Geological Survey in cooperation with the Texas Board of Water Engineers to determine the capacities of the formations to yield water to wells. The most reliable index of the quantity of water that a formation will yield has heretofore been considered to be the empirical correlation of pumpage and water levels in wells. Studies of recharge, laboratory studies of permeability and specific yield of water-bearing materials, and measurements of specific capacities of wells have also proven valuable.

With the development of new methods, pumping tests have recently come into use. A pumping test and the use of its results are essentially a process of obtaining for the formation under investigation the equation of a water-level drawdown curve for a short period of time and extending the curve over a longer period by means of the equation. Predictions may thus be made of drawdowns caused by given rates of pumping. In making the predictions computed drawdowns must be adjusted for boundaries and changes in character of the formation not taken into account by the equation determined with the pumping test. Pumping tests have been made at Houston, Lufkin, Camp Swift, South Camp Hood, North Camp Hood, and Sweeny. The methods of making the tests, the results, and the use of the results are briefly described in this paper.

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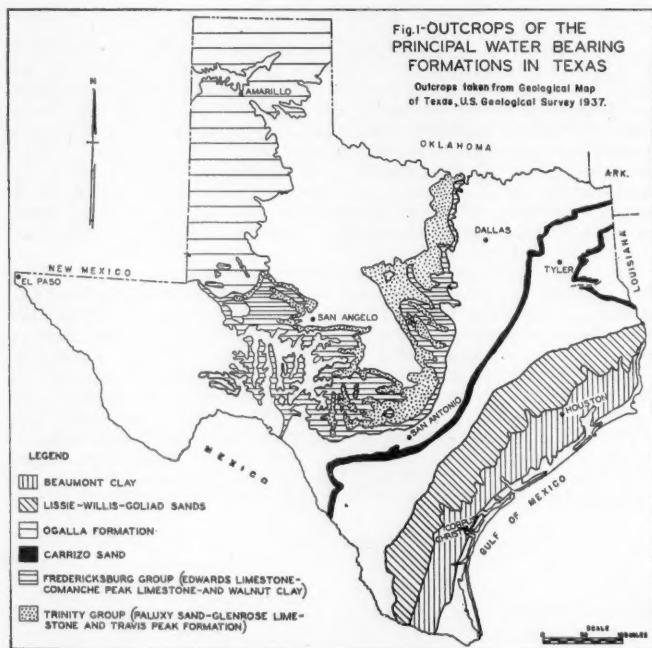
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## INTRODUCTION.

LARGE quantities of ground water have been obtained from wells in Texas at a steadily increasing rate for many years. In the last seven years the increase

<sup>1</sup> Published with the permission of the Director of the Geological Survey, United States Department of Interior.

in withdrawals has been exceptionally large due to industrial and irrigation expansion in several parts of the state. The major part of the water is derived from comparatively few aquifers (see Fig. 1), the more important of which, from the youngest to the oldest, are the sands in the Beaumont clay of Pleistocene age, the sands of the Lissie, Willis and Goliad formations (undifferentiated in wells) of Pleistocene and Pliocene age, the Ogallala formation of Pliocene age, the Carrizo<sup>1</sup> sand of Eocene age, and the Edwards



limestone and the Travis Peak formation of Lower Cretaceous age. Less important aquifers are the outwash (bolson and lake) deposits of Quaternary age, the sands in the Lagarto clay of Miocene (?) age, the Oakville sandstone and the Catahoula sandstone of Miocene age, the Sparta sand and the sands of the Wilcox group of Eocene age, the Woodbine sand of Upper Cretaceous age and the Paluxy sand of Lower Cretaceous age. With the exception of the Edwards limestone all the important aquifers consist of sand, sandstone, or sand and gravel.

The following table shows most of the areas in which the withdrawal by wells is 3,000,000 gallons a day or more (see Fig. 2), the formation or group

<sup>1</sup> The Carrizo sand of northeastern Texas, according to L. W. Stephenson, may not be of the same age as the Carrizo sand of the type area in Dimmit County, southern Texas.

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of formations comprising the aquifer, the approximate average daily withdrawal in millions of gallons in 1943, and the use of the water:

WITHDRAWALS OF WATER IN AREAS OF LARGE USAGE.

Area	Aquifer	Approximate average daily withdrawal (million gallons) 1943	Principal use of water*
South High Plains	Ogallala formation	270	Irr, P
Houston	Lissie, Willis and Goliad formations and Lagarto clay	100	Ind, P
San Antonio	Edwards limestone	100	P, Ind, Irr, M
Katy	Lissie, Willis and Goliad formations	50	Irr
Jackson-Wharton-			
Matagorda Counties	Lissie, Willis and Goliad formations	35-40	Irr
Winter Garden	Carrizo sand	40	Irr
North High Plains	Ogallala formation	25	Ind, P
El Paso	Outwash (bolson) deposits	20	P, M
Texas City	Beaumont clay	15	Ind, P
Baytown	Beaumont clay	15	Ind, P
Fort Worth-Dallas	Woodbine sand, Paluxy sand, and Travis Peak formation	15	Ind, M, P
Galveston	Beaumont clay	12	P, M
Pecos	Outwash (bolson and lake) deposits	15	Irr, P
Lufkin	Carrizo sand	7	Ind
Kingsville	Lissie and Goliad formations	5	P, Ind, M
South Camp Hood	Travis Peak formation	4	M
North Camp Hood	Travis Peak formation	3	M
Camp Swift	Wilcox group	3	M
Orange-Nederland	Beaumont clay	3	P, Ind, M
Falfurias-Premont	Lissie and Goliad formations	3	Irr, Ind
Sweeny	Beaumont clay	3	Ind

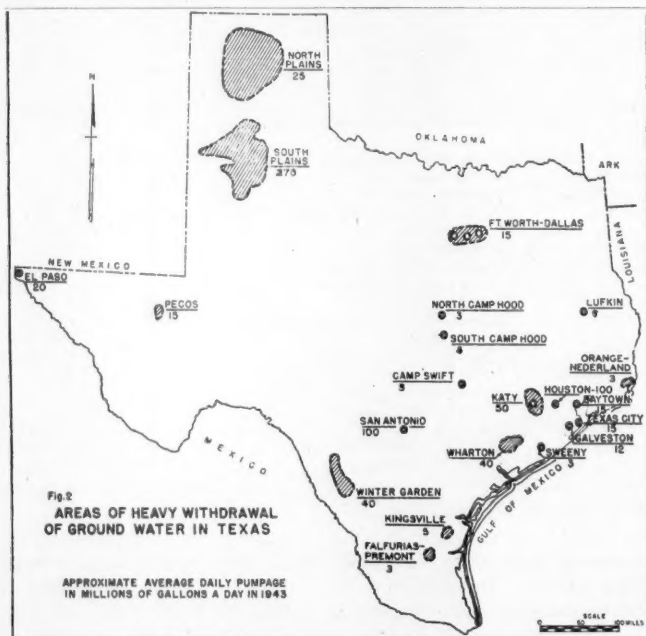
\* Ind, industrial; Irr, irrigation; M, military; P, public supply.

The average daily withdrawal from the 21 areas is estimated to be about 750 million gallons. In addition to the withdrawals listed in the table more than 500 towns and cities, ranging in population from a few hundred to 16,000, and a large number of war plants depend on wells for their water supplies. With the exception of the Ogallala formation of the High Plains area all of the aquifers occur under artesian conditions in the areas of heavy withdrawal.

The present investigation of the ground-water resources of Texas by the Geological Survey was begun in September 1929 and is made possible by appropriations by the State Legislature and several local agencies for co-operative work by the State Board of Water Engineers and the Federal Survey. This work has from the beginning been under the direct supervision of W. N. White, Senior Hydraulic Engineer, and the general supervision of O. E. Meinzer, Geologist in Charge of the Division of Ground Water. During the 14 years in which this investigation has been continued ground-water studies have been made in nearly every part of the state.

In nearly every area investigated where large quantities of water are pumped, continuing records of pumpage have been kept and depths to water

have been measured periodically in selected observation wells. The records of pumpage and water levels have been correlated for the purpose of determining the amounts and rates of drawdowns of the water levels in wells produced by withdrawals from the aquifers. In addition, a large program of measuring depths to water in wells penetrating important aquifers in areas of potential development was initiated and has been continued and expanded.



One type of correlation of pumpage and water levels which has been easy to obtain is the specific capacity of a well, or the relation between the rate of pumping from the well and the drawdown of the water level in it. Although the specific capacities determined have been valuable, they have been used to compare formations only with caution and to supplement other data, for the specific capacity of a well is often affected as much by the construction of the well and the degree to which it is developed as by the characteristics of the formation.

Theoretical methods based on Darcy's law for estimating drawdowns of water levels have been available for many years, but until recently the highly impracticable assumptions and the lack of development of the methods have prevented their use on a wide scale. In 1925, however, Meinzer (1) advanced the theory of elasticity of an artesian aquifer; and in 1935 Theis (2)

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developed the non-equilibrium formula from the analogy of the flow of ground water to the flow of heat, which includes elasticity and time in the determination of the drawdown of water levels caused by pumping. In 1939 Jacob (3) derived the same formula from basic concepts of hydraulics and mechanics. Practical applications of this formula have since been made in several parts of Texas to estimate drawdowns, the first step in the application usually being to make a pumping test and the next step to use the results of the test with the formula to predict long-term drawdowns.

#### PUMPING TESTS.

The Theis non-equilibrium formula (2) is:

$$s = \frac{114.6Q}{T} \int_{\frac{1.87r^2S}{4t}}^{\infty} \frac{e^{-u} du}{u}$$

where  $s$  is the drawdown, in feet, at any point in the vicinity of a well pumped at a uniform rate;  $Q$  is the discharge of the well, in gallons a minute;  $T$  is the coefficient of transmissibility of the aquifer;  $r$  is the distance from the pumped well to the point of observation, in feet;  $S$  is the coefficient of storage of the aquifer; and  $t$  is the time the well has been pumped, in days.

The coefficient of transmissibility is defined (4) as the number of gallons of water that will move in one day through a vertical strip of the aquifer one foot wide and having the full height of the aquifer with a hydraulic gradient of 100 per cent.

The coefficient of storage is defined (4) as the volume of water, measured in cubic feet, released from storage in each vertical column of the aquifer having a base one foot square when the artesian head is lowered one foot.

The non-equilibrium formula assumes that the aquifer is infinite in extent, that it is homogeneous and its transmissibility is the same at all places, and that it is bounded by impermeable beds above and below. It further assumes that the coefficient of storage is constant, and that the water is released from storage instantaneously with a decline in artesian head.

The coefficients of transmissibility and storage of an aquifer are determined by the non-equilibrium formula from a pumping test and may be applied to estimating future drawdowns of water levels. This is essentially a process of determining the equation (the Theis non-equilibrium formula with the proper coefficients) of a water-level drawdown curve for a short period of time and extending the curve over a longer period of time by means of the equation.

To determine the coefficients of transmissibility and storage from a pumping test the effect of a measured change in the rate of pumping from a well on the water levels in it and in other wells is first obtained. The non-equilibrium formula may then be applied in any one of three ways to obtain the coefficients: (1) to the drawdown or recovery of water levels in at least two observation wells at any particular time after the change in the rate of pumping occurred; (2) to the amount and rate of drawdown or recovery in a single observation well; or (3) to the rate of recovery in a well when pumping from the well is stopped. Both coefficients are obtained by the use of

either of the first two methods, while the last-mentioned method is used only to determine the coefficient of transmissibility.

The coefficient of transmissibility may also be determined from the Thiem formula (5), which is, for artesian conditions:

$$T = \frac{527.7Q \log_{10} \frac{a_1}{a}}{(s - s_1)}$$

where  $T$  is the coefficient of transmissibility;  $Q$  is the rate of pumping, in gallons a minute;  $a$  and  $a_1$  are the distances of two observation wells from the pumped well, in feet; and  $s$  and  $s_1$  are the respective drawdowns, in feet, of the water levels in the two observation wells. This formula is applied to the drawdown or recovery of water levels in two observation wells at a time after pumping has been continued or discontinued long enough to allow the water levels in the two wells to decline or recover at the same rate.

Theoretically, it is only necessary to determine the coefficients in one pumping test, for the principal assumption of the non-equilibrium and Thiem formulas is that the coefficients are constant throughout the aquifer. However, in practice it is found that the computed coefficients determined from each combination of wells are usually different from one another, the amount depending upon the variations in the geologic conditions.

The ideal way to make a pumping test is, therefore: to choose a well that can be pumped at a large rate and can be shut down at will, and which is a considerable distance from any other pumped wells; to install a large number of observation wells in all directions and at varying distances from the well to be pumped; and to pump and shut down the well and make water-level measurements in all the wells to obtain representative drawdown and recovery curves. The manner in which tests usually have been made in Texas, however, has been to pump or shut down one of a group of heavily-pumped wells for a limited time and to observe the effect of the change on the water levels in any other wells that are idle and are available for observation. Usually not more than two or three observation wells have been available. Often the only water-level observations that can be made are of the recovery of the water level in the well which has been pumped and shut down for the test.

The length of a test, or the period of time the well is pumped or shut down, has ranged from only a few minutes to almost two weeks, while the average test lasts from one to five days. The rate of pumping from all wells in the vicinity is kept as constant as possible for some time before the test. During this period measurements of depth to water are made in the observation wells to determine any trend the water levels may be taking in an upward or downward movement caused by previous changes in the rate of pumping. When this trend is determined, the well around which the test is to be centered is turned on or off and water-level measurements are continued in it and in the other observation wells. Drawdown or recovery curves of water levels are obtained and adjusted to eliminate the upward or downward trend caused by previous changes in pumping. Where a wide coverage is desired in a well field, another test using another combination of wells is begun as soon as one

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test ends. Usually the procedure is to alternately shut down one well and turn on another. When as many tests as are desired, or can be made practically, are completed, they are analyzed by the non-equilibrium and Thiem formulas to obtain the coefficients of transmissibility and storage. These coefficients are weighted and the average coefficient determined for the aquifer in and near the well field.

In applying the results of pumping tests, an axiom in using the coefficients to estimate drawdowns in a field containing several pumped wells is that the pumping from each well causes a drawdown of water level in the well itself and in each of the other wells drawing from the same aquifer. The total amount of drawdown in any well is the sum of the drawdowns caused by all the pumped wells. The magnitude of that part of the drawdown in a well caused by any one pumped well is not affected by the magnitude of the drawdown caused by the other pumped wells.

Steps involved in estimating drawdowns are as follows: (1) the determination of the drawdown caused by developing a hydraulic gradient through the "well-face" and through the aquifer immediately surrounding each pumped well; (2) the determination of the drawdown caused by developing the proper gradients through the aquifer in the rest of the well field and immediately surrounding it, for which average coefficients have been obtained; (3) the determination of the drawdown caused by developing the necessary gradients through the remainder of the aquifer to its boundaries; and (4) the adjustment of the drawdown computed with the average coefficients under (3) to account for changes in thickness and character of the aquifer and for boundaries such as outcrops, areas of natural discharge, faults, and other breaks in the continuity of the aquifer.

The drawdown in a well is computed with the non-equilibrium formula, except for that part of the drawdown caused during the first few hours of pumping by the well itself. This part of the drawdown is that mentioned under (1) of the preceding paragraph and, if computed, may be in error because: it is difficult to determine the effective radius of the well; Darcy's law may not hold near the well because of the high velocities; the permeability of the well screen may not be the same as that of the sand; the well may not be thoroughly developed; and it may not penetrate the total thickness of the sand. For these reasons the specific capacity of the well, which is obtained from the actual drawdowns, is usually used in determining the drawdown caused by the well in itself during the first day of pumping. This eliminates the errors that might be encountered by the use of the non-equilibrium formula.

The computations of drawdown caused by the pumped well in itself during the rest of the period for which computations are desired are made with the non-equilibrium formula. Also, all computations of drawdowns in the well caused by pumping other wells are made with the non-equilibrium formula for the entire period.

As stated, the non-equilibrium formula assumes an aquifer of infinite areal extent, and values obtained by its use must be adjusted for the effects of boundaries, such as outcrops or faults. In wells far from boundaries the

decline of the water levels is not influenced by the positions of the boundaries for a considerable length of time after pumping is begun, sometimes for as long as several years; but, as time goes on, the boundaries become more and more the determining factor in the rate of decline. Replenishment from the area of recharge tends to decrease the rate of decline caused by pumping from wells while faulting or the lensing out of the aquifer has the opposite effect and tends to increase the rate of decline. The length of time required for the position of the boundary of an aquifer to affect the decline of water levels increases with the distance of the boundary from the wells, and the amount of the effect decreases with the distance.

In adjusting the computed drawdowns for the effect of an outcrop, it is assumed that the outcrop is a straight line of infinite length and that the water table along the line remains at essentially a constant level. A hypothetical image recharge well of the same production as each real well is assumed to be placed on the other side of the outcrop line so that it is directly opposite the real well and is the same distance from the line as the real well. The adjusted drawdown of water level in a real well is the algebraic sum of the computed drawdown caused by pumping the real wells and the computed rise in water level produced by the hypothetical recharge wells, these being determined by the non-equilibrium formula. The limiting condition, that the water level does not decline at the outcrop, is thus fulfilled, for the computed decline at the outcrop will always be zero. The same method of adjusting for a fault or pinching-out of the aquifer is used, except that the hypothetical image well is a discharging well instead of a recharging well, and the adjusted drawdown at the boundary line is twice the drawdown computed for an infinite aquifer.

Estimated adjustments of drawdowns are made for aquifers that have definite variations in thickness and character outside the well field which are not taken into account by the average coefficients determined for the field. These adjustments are made partly by the image well theory and partly by using Darcy's law to estimate the hydraulic gradients required through each area of the aquifer. The amount of adjustment depends on the magnitude of the variations in the aquifer.

When the final estimates of drawdowns of water levels caused by pumping are made, with all adjustments that can be made, they must be used with caution and with a knowledge of how well the assumptions of the formula and the adjustments are fulfilled. They can be extremely valuable if used in this way, but can be very misleading if applied indiscriminately.

After pumping is begun, it is good practice to keep periodic records of water levels and rates of pumping so that estimates can be checked and revised if necessary. Usually, the rates of pumping under actual conditions are not exactly the same as those used in the computations and it is necessary to recompute and readjust the theoretical drawdowns to obtain comparable figures.

#### APPLICATION OF PUMPING TESTS IN TEXAS.

In the fall of 1939 C. E. Jacob, of the Geological Survey, conducted a series of pumping tests at the Houston municipal well field and the city-

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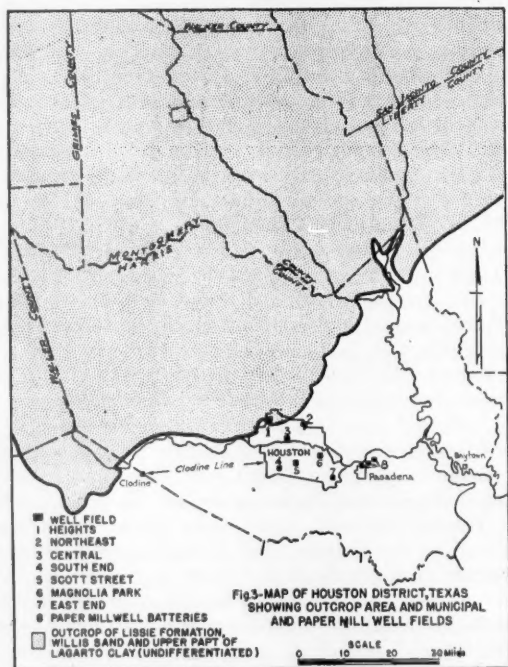
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owned observation wells. They were the first pumping tests based on the non-equilibrium formula to be made in Texas. The coefficients obtained from these tests varied over a wide range, principally because of the variation in thickness and character of the water-bearing sands and their associated clays. Following these variable results, no more pumping tests were made in Texas until the summer of 1941, when an investigation of the ground water in the Carrizo sand in the Lufkin area was begun. In making plans for this study it was thought that since the Carrizo sand was relatively uniform in character, thickness, and extent it would be as ideal as any other formation in Texas for the application of the non-equilibrium formula. Therefore, a series of pumping tests was made on the wells of the Southland Paper Mill during August and September 1941. The coefficients obtained from the individual tests were remarkably uniform, and the non-equilibrium and Thiem formulas each gave about the same coefficients of transmissibility. Also computed long-term declines of water levels compared favorably with actual declines. Based principally on the results of these tests it was concluded that the non-equilibrium formula could be used to great advantage with favorable geologic conditions. During 1942 and 1943 detailed pumping tests were made on wells at Camp Swift, South Camp Hood, North Camp Hood, and Sweeny, and on wells in another formation at Lufkin. Many short tests were made on one or more wells in several parts of the state. In addition to using the results of these tests to predict future draw-down of water levels, they have been used to determine the proper spacing and capacity of wells and depth of pump settings, and to determine the practicable amount of water that can be withdrawn from an aquifer.

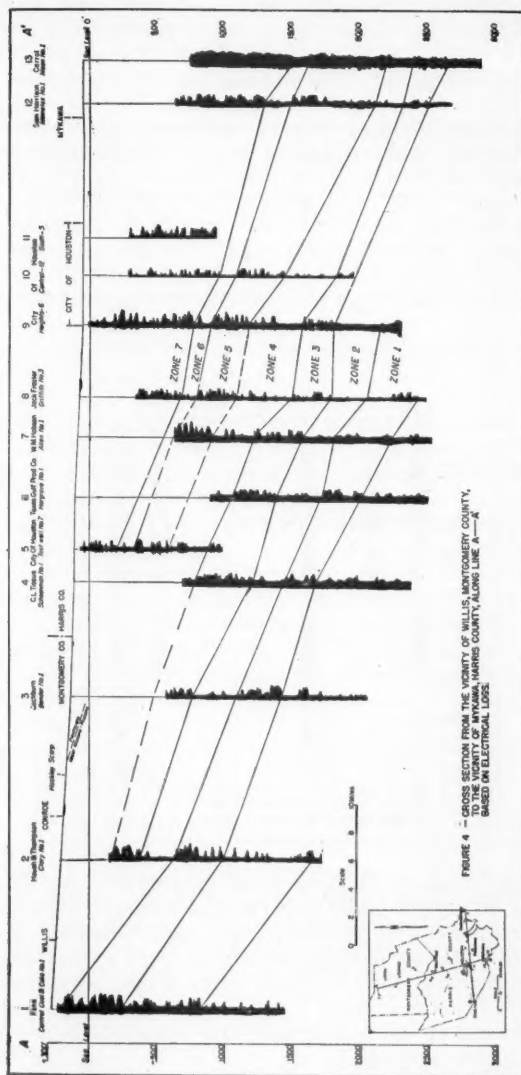
The seven series of detailed tests which have been made and are described in the following paragraphs of this paper cover a considerable range of geological and hydrological conditions. At Houston the aquifer is made up of extremely irregular and lenticular deposits of sands interbedded with beds of clay. The total thickness of the water-bearing sands averages about 600 feet. At Lufkin the Carrizo sand is comparatively uniform in thickness and character over a wide area, but the continuity of the outcrop is broken by faulting. At Camp Swift the aquifer is cut by a fault within the well field, and almost no effect on the water levels is caused by the pumping of wells on the opposite side of the fault. Also the wells are close to the outcrop of the sands. At Camp Hood the sands thicken eastward and thin westward, and the lower sands do not outcrop at the surface but terminate in the up-dip direction against the underlying formations. The wells are about 40 miles from the outcrop. At Sweeny the aquifer is relatively uniform in thickness, occurs near the surface, and outcrops within 5 miles of the well field. The Sparta sand in the Lufkin area is irregular in thickness and character and occurs partly under water-table conditions and partly under artesian conditions.

*Houston District.* The Houston district comprises Harris County west of the San Jacinto River and adjoining parts of Montgomery, Waller, and Fort Bend Counties (see Fig. 3). It is a plain of low relief that lies not far above sea level, and is a part of the West Gulf Coastal Plain. Large quan-

ties of ground water are pumped in the district from three areas: (1) the Houston area, which includes the city of Houston and the areas immediately adjacent, except on the east; (2) the Pasadena area, which includes the industrial section that extends along the ship channel from the Houston city limits eastward to Deer Park; and (3) the Katy area, which is a rice irrigation area of about 500 square miles roughly centered at the town of Katy, 30 miles west of Houston.



The geologic formations from which the district obtains its water supply are the Lagarto clay of upper Miocene (?) age, the Goliad sand of Pliocene age, the Willis sand of Pliocene (?) age, and the Lissie formation of Pleistocene age (6). The formations crop out in a belt about 60 miles in width parallel to the coast and at a distance of about 50 miles from it. They dip southeastward, and thus successively younger formations crop out from northwest to southeast. The dip of the beds in the formations is variable but in general increases with depth. The estimated dip of the older beds is about 50 to 60 feet to the mile, and of the younger beds about 20 feet to the mile, showing a thickening of the formations down dip.



The formations consist of zones that are predominantly sand and zones that are predominantly clay. The "sand zones" are made up of extremely irregular and lenticular deposits of sand, pea gravel, sandy clay, and clay. The sands are interbedded and intergraded with thin beds and layers of clay, sandy clay, and pea gravel. The interfingering layers and lenses grade into one another laterally and vertically in short distances. The thinner beds in many places change character or pinch out within a few hundred feet (see Fig. 4). The "clay zones" consist of mottled calcareous massive clay con-

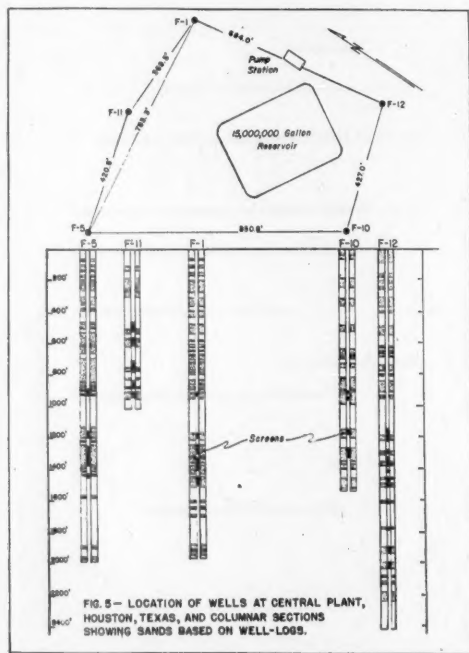


FIG. 5—LOCATION OF WELLS AT CENTRAL PLANT, HOUSTON, TEXAS, AND COLUMNAR SECTIONS SHOWING SANDS BASED ON WELL-LOGS.

taining numerous calcareous nodules and interbedded with thin beds and lenses of fine- to medium-grained sand and sandstone. In general the clays are poorly stratified and are persistent only for short distances, although a few of the zones in which clay predominates can be traced throughout the district.

Since no diagnostic fossils have been found in these formations and there is very little definite information available on the subsurface correlation of the formations and on the relationship of the subsurface beds with the outcrop, the best data available for the study of the strata are furnished by electrical logs of oil tests and water wells. The upper Miocene, Pliocene, and Pleistocene section has been subdivided into seven zones based on electrical logs, as shown by the cross-section in Fig. 5. Zones 1, 3, 5, and 7 are



predominantly sand and zones 2, 4, and 6 are predominantly clay. Most of the ground water withdrawn from wells in the Houston district is derived from zones 5 and 7; however, a few of the deeper wells draw from the upper part of zone 3. In the city of Houston and areas to the east, south, and west the water contained in the sands in zone 1 and the lower part of zone 3 is too highly mineralized for most uses. Logs of wells and test holes show that there is an average of about 600 feet of fresh water-bearing sands in Houston and adjoining areas, and along a line of test holes from the western city limits to Clodine, approximately 16 miles to the west.

Nearly all the water pumped in the Houston and Pasadena areas comes from approximately 300 wells. The estimated average quantity of water pumped in the two areas in 1930 was about 50 million gallons a day. From 1930 to 1936 the rate of pumping was more or less constant. In 1937, however, the pumpage increased to 70 million gallons a day, due to a large industrial development at Pasadena; and from 1939 to 1943 it was 72, 78, 77, 85, and 95 million gallons a day.

The water levels in wells in the two areas in 1931 were between 50 and 80 feet below the land surface. From 1931 to 1937 they remained practically constant, but the large increase in the rate of pumping in 1937 caused a marked decline. The decline began almost immediately in observation wells in and near Pasadena, while in more distant wells it was less rapid. In some wells in the central and western parts of Houston several months elapsed before the decline resulting from the new pumpage was noticeable. Inasmuch as several years are required, because of the great distance to the outcrops of the aquifer, before the water levels in the wells can reach equilibrium after an increase in pumping, and since the rate of pumping in the areas has more or less continuously increased since 1937, the water levels throughout the areas have continued to decline since 1937. The average decline in observation wells in the Houston and Pasadena areas has been approximately 65 feet since 1936.

Although a large amount of pumpage and water-level records are available for the Houston district, and it has been possible for many years by the use of their empirical correlations to estimate fluctuations of water levels caused by new changes in pumpage, it has been thought that more theoretical data could be used to considerable advantage. Therefore, in the fall of 1939 C. E. Jacob (7) conducted 16 pumping tests at the Houston municipal well fields and 5 tests on the city-owned observation wells. Each test consisted of pumping a well at a measured rate for a given length of time and then stopping the pump, and observing the rate of recovery of the water level in the well. In many cases, nearby wells screened in the same sands were turned on or off during the recovery period, and their interference with the recovery was observed. Jacob analyzed the results of these tests by means of the non-equilibrium formula.

The field coefficients of permeability (coefficients of transmissibility divided by the thickness of the sands drawn from) determined from the tests range from 180 to 400 and average about 300. With this permeability, and an average thickness of all the water-bearing sands of 600 feet, the co-



efficient of transmissibility of the water-bearing sands supplying Houston is computed to be 180,000.

The coefficients of storage determined from the tests range from 0.000165 to 0.00108 and average about 0.0005 for thicknesses of sand from 157 to 400 feet. The average thickness of the sands drawn upon in the tests is about 300 feet. As the coefficient of storage is considered approximately proportional to the thickness of the aquifer, a coefficient of 0.0005 for 300 feet is equivalent to 0.001 for a thickness of 600 feet.

An effort was made to evaluate the coefficients of transmissibility and storage determined by Jacob, by using the adjusted values with the non-equilibrium formula (8). Drawdowns were computed which theoretically should have occurred in 25 observation wells at periods of one and two years after the rate of pumping from all the sands was increased by 17 million gallons a day at Pasadena in 1937. Except for one well, the computed drawdown at the end of one year is much more than the actual decline of water levels, which ranged from a rise of 1 foot to a decline of 31 feet. For the two-year period, the computed drawdown is also larger than the actual decline, which ranged from 4 to 32 feet. However the difference between the actual and computed figures is not as large, in proportion to the actual decline, for the two-year period as at the end of the first year. Wells at approximately the same distance from Pasadena had widely different declines during the two-year period. Most of these differences can be explained only by the fact that the wells draw from different sands in the aquifer, or are located in different directions from Pasadena. The record on the whole, therefore, seems to indicate that the individual beds of sand vary widely in transmissibility, and some of the beds are much more closely interconnected than others.

Theoretically, each of the 25 two-year water-level drawdown curves could be analyzed by the non-equilibrium formula to determine the coefficients of transmissibility and storage of the aquifer. However, only eight were found to conform to theory enough to give reasonable results. Eight of the others were probably affected by local pumping; the anomalies in the remaining nine can be accounted for only by the heterogeneous character of the aquifer. The coefficients of transmissibility and storage computed from the eight curves which can be analyzed may be divided into three groups of closely comparable figures, each group representing wells in a different locality. The coefficients of transmissibility for four wells in east Houston range from 125,000 to 133,000; for two wells in north Houston, they are 112,000 and 119,000; and for two wells in west Houston, they are 173,000 and 196,000. The average of all the coefficients is 140,000. The coefficient of storage for the 4 wells in east Houston range from 0.0041 to 0.0054; for 2 wells in north Houston they are 0.0021 each; and for 2 wells in west Houston, they are 0.0016 and 0.0019, respectively. The average of all the coefficients is 0.0033. The average for transmissibility is not greatly different from the adjusted value determined from Jacob's tests, but the average for storage is approximately three times his adjusted value.

The large discrepancy between the storage coefficients determined from

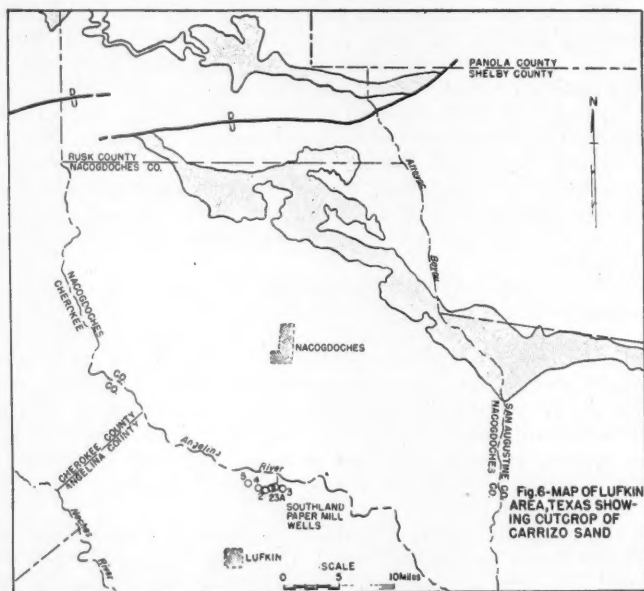
the short pumping tests and the two-year water-level declines seems to indicate that the time element involved makes a great difference in the coefficient of storage that is obtained for the aquifers at Houston. An explanation for this is that the clays above and below a water-bearing sand and interbedded with it probably give up considerable water for a long time after the artesian head within the sand is lowered. Another reason for the discrepancy between the average storage coefficients may be that Jacob's tests were made in well fields where the head had fluctuated many times through the range recorded, whereas the water levels in observation wells used to evaluate his results were lower than they had ever been before, and therefore were declining through that range in head for the first time. It has been found in the study of soil mechanics that in many cases sands and clays, which are under a constant load and which have been compressed by a reduction in internal hydrostatic pressure, do not expand to their original volume when the pressure is increased to its original amount. Therefore, after water is once removed from storage within a sand and its adjacent clay beds as a result of a decline in artesian head, the beds may not again take into storage, with a comparable rise in head, as much water as was released with the decline. If so, they also will not release as much water with a second decline as with the first.

Because the coefficients of transmissibility and storage determined from the pumping tests and the long-term drawdowns of water levels vary over such a wide range, whereas the non-equilibrium formula assumes that the coefficients are constant, it is believed that the formula should not be used in the Houston district with average coefficients to predict drawdowns over a wide area and in wells drawing from different parts of the aquifer. Furthermore, it is believed that it is practically impossible in an area such as the Houston district, where the clays and sands are so closely interbedded and lenticular in extent, to obtain the average coefficients for the many aquifers drawn upon or for all parts of any one aquifer.

The non-equilibrium formula, therefore, has more of a "qualitative" value in the district than a "quantitative" one. The theory of elasticity upon which it is based has been of great help in determining the reasons for many fluctuations of water levels difficult to interpret. Also, the formula has been used to compute theoretical drawdowns caused by proposed pumping, which, though probably in error, are valuable in comparing the merits of various arrangements of proposed wells. In connection with the contemplated installation of new wells at considerable distances from the present centers of pumping, estimates have been made of the relative drawdowns at given points with various hypothetical changes in pumping rates. A proposed plan of development by the City of Houston includes 16 wells, with a maximum total production of 48 million gallons a day, to be drilled along a line from the western city limits of Houston to Clodine. The first unit of this development, which consists of six wells, will be started in 1944. The non-equilibrium formula has been used as an aid in determining the spacing and production of the proposed wells. It has been used also in making estimates of the relative merits of various arrangements of pumping within the city.

By using the average of all the coefficients of transmissibility and storage that have been determined, the rate of inflow and the amount of water taken from artesian storage in areas of heavy withdrawal have been estimated. Though probably only correct in their order of magnitude, the estimates show that withdrawal of water from storage in these areas is relatively small in comparison to the total amount pumped.

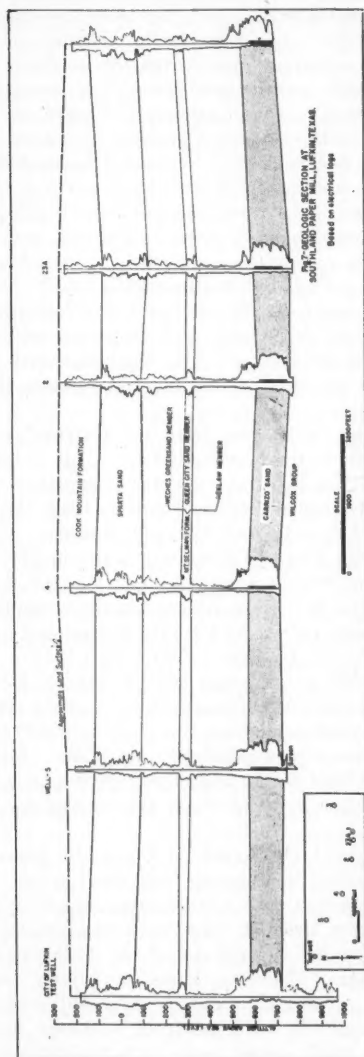
*Lufkin Area (Carrizo sand).* The Lufkin area (see Fig. 6), which includes Angelina and Nacogdoches Counties, lies on the southeastern flank



of the east Texas syncline. Practically all the water supplies in the area come from the Carrizo sand, which contains water of better quality and is more productive than any other water-bearing formation in the area.

The Carrizo sand lies conformably below the Reklaw member of the Mount Selman formation and unconformably above the Wilcox group. All are of Eocene age. The Carrizo consists of loosely-cemented moderately coarse-grained sand with thin lenses of clay and sandy clay. The sand is composed principally of rounded and subangular grains of quartz that average about one millimeter in diameter. The formation is rather uniform in thickness, ranging from 122 to 154 feet in the six Southland Paper Mill wells and the two City of Lufkin wells, and averaging about 140 feet (see Fig. 7).

The Carrizo sand dips to the south at an average rate of about 50 feet to the mile in this area. According to electrical logs of water wells and oil



tests the formation is continuous throughout the area and extends down dip a great distance beyond the area.

The formation crops out in a gradually widening belt, extending north-eastward from the Louisiana border across the northern part of Sabine and San Augustine Counties and the northern part of Nacogdoches County (see Fig. 6). The continuity of the outcrop is broken in southeastern Rusk County on the edge of the east Texas syncline by a zone of faulting that has an eastward trend. The faulting is by normal faults and the downthrow is to the north and northwest. The maximum vertical displacement, which occurs near the center of the zone, is approximately 500 feet. Horizontally the outcrop is displaced about 25 miles to the east, and from this point it extends to the northeast along the east flank of the syncline. It is not known whether the faulting extends into the formation for any considerable distance down dip from the outcrop. To the west the formation dips under the younger formations into the syncline and crops out on the west side of the syncline in a narrow belt that extends southwestward into South Texas. The closest point on this part of the outcrop is more than 80 miles from Lufkin.

Most of the water withdrawn from the Carrizo sand in this area is pumped from the wells of the Southland Paper Mill and the cities of Lufkin and Nacogdoches. Pumping from the five production wells of the paper mill was started in December 1939 and during 1940, 1941, 1942, and 1943, it averaged 4.5, 5.5, 5.2, and 4.8 million gallons a day, respectively. Pumping from the well of the City of Lufkin was begun in May, 1939, and during 1940, 1941, 1942, and 1943 it averaged about 0.5, 0.8, 1.0, and 1.2 million gallons a day, respectively. Nacogdoches has been supplied from two wells in the Carrizo for many years, and the rate of pumping from them averaged about 0.6 million gallons a day from 1939 through 1943.

During most of 1940 and the first eight months of 1941 the water levels in the wells in the area declined at practically a constant rate. Near the wells of the paper mill the decline amounted to more than 100 feet, while near the outcrop of the Carrizo it was practically negligible. Since the summer of 1941, however, there has been no appreciable decline in wells near the paper mill, although the decline in wells nearer the outcrop has amounted to about two or three feet.

In the summer of 1941, the Southland Paper Mill began to investigate the possibilities of increasing its pumpage from the Carrizo sand to 10 million gallons a day in connection with a large program of expansion of the mill. At that time the water levels in their wells and nearby observation wells were still declining rapidly, and the end of the decline could not be forecast from the available data. Therefore, it was tentatively concluded that additional pumping from or near the existing paper mill wells would be unwise unless data which might be obtained from proposed pumping tests could prove that the water levels would soon reach equilibrium with the existing rate of pumping. A series of 10 pumping tests was made on the five production wells and test well 23A of the Southland Paper Mill during August and September, 1941 (9). In these tests three or more of the wells were pumped

to supply the mill, and observations were made of fluctuations of the water-levels in the idle wells produced by changes in the rate of pumping, which was adjusted to range between about 3,700 and 5,800 gallons a minute by turning one or more wells on or off. The length of a test, or the time during which the pumping was maintained at a given rate, varied between one and ten days, depending on the distance between the pumped and observation wells and the methods being applied for determining the coefficients.

The water-level drawdown and recovery curves obtained from the tests were analyzed by the Thiem and non-equilibrium formulas. Eight coefficients of transmissibility obtained by the use of the Thiem formula range from 31,500 to 36,000 and average 33,100. Ten coefficients of transmissibility obtained with the non-equilibrium formula range from 30,600 to 34,100 and average 32,300. Seven coefficients of storage range from 0.000120 to 0.000160 and average 0.000138. The coefficients of transmissibility and storage obtained from the individual tests agree with one another remarkably well. The Thiem and non-equilibrium formulas each give about the same coefficients of transmissibility. This agreement checks with the geologic data in showing that the Carrizo sand is remarkably uniform in thickness and character, thereby fulfilling the most important assumptions upon which the formulas are based.

Near the end of the tests the paper mill was shut down for a week for general repairs, and pumping was practically discontinued from the wells. During the shutdown and the 12 succeeding days, water-level measurements were made in the paper mill wells and in several observation wells at distances of several miles from the nearest mill well. The recoveries and drawdowns thus determined compare very favorably with values computed by the non-equilibrium formula using the average coefficients, the average difference between the actual and computed figures being less than 10 per cent.

The non-equilibrium formula has also been used with the average coefficients to compute the declines in water levels which should have occurred in observation wells in the area between 1939 and 1941. Little data are available on the levels in the wells before pumping by the City of Lufkin and the paper mill began, but periodic measurements have been made since early in 1940, and the actual declines of water levels during 1940 and 1941 shown by the measurements agree very closely with the computed declines for this period, no two differing by much more than 10 per cent.

Because of the close agreement of the various coefficients determined from the tests and of actual and computed water-level declines, it was concluded in 1941 that the non-equilibrium formula could be used to predict rather accurately future drawdowns of water levels that would be caused by maintaining the rates of pumping at that time and by increasing those rates, provided that allowances would be made in the estimates for the boundaries of the formation.

As far as can be determined there are no boundaries of the Carrizo sand near the Lufkin area except the outcrop and the zone of faulting which breaks the outcrop on the edge of the East Texas syncline. For practical purposes the syncline and faults may cause the absence of the outcrop to the



west. By methods devised by Theis (10) and Muskat (11) it has been determined that the computed drawdown at equilibrium, assuming an infinite line-source, caused by the paper mill's pumping must be increased by about 15 to 20 per cent to make up for the lack of the outcrop to the west.

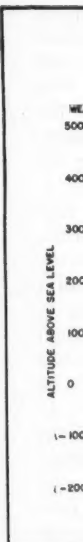
In the fall of 1941 engineers of the paper mill used the non-equilibrium formula with the average coefficients of transmissibility and storage determined from the pumping tests to compute the drawdowns which might be expected in the wells as a result of continuing pumping at the existing rate and of increasing this rate by approximately 100 per cent. The water levels in a large number of wells have been observed as a check against the computations. The computations showed that drawdowns after the fall of 1941 that would be caused by continuing the existing rate of pumping would be negligible, and they have been. This has allowed the paper mill to plan to obtain the needed additional five million gallons a day merely by lowering the pumps in the present five wells, instead of drilling new wells at a considerable distance away from the present wells. Pumping at the increased rate was begun in the spring of 1944, and a careful record of drawdowns of water levels is being kept as a check against the computed values. The cities of Lufkin and Nacogdoches and the several smaller users of water from the Carrizo sand were notified of the coming decline so that the pumps in their wells could be lowered if necessary in plenty of time to avoid a shortage of water.

*Camp Swift.* Camp Swift is about five miles north of the city of Bastrop in Bastrop County, Texas. The surface of the area is steeply rolling except for the broad and rather shallow valley of the Colorado River, which cuts across the central part of the county a few miles south of the camp. The altitude ranges from about 300 feet in the bed of the Colorado River to about 600 feet on the highlands.

Camp Swift obtains its water supply from seven wells (see Fig. 8) drawing from an artesian sand zone occurring between depths of about 250 to 600 feet below the surface. The zone belongs to a formation named by Plummer the Rockdale formation of the Wilcox group, of Eocene age, and occurs at about the middle of the formation. The thickness of the zone is reported to be about 250 to 300 feet, but approximately 500 feet of sand was penetrated in well 7. The zone consists of rather thick beds of fine- to medium-grained sand interbedded with layers and lenses of clay, sandy clay, and silt. Varying amounts of lignite are present throughout. The top of the sand zone has tentatively been mapped as cropping out about three miles northwest of the camp well line. The outcrop is roughly parallel to the well line, extending in a northeast-southwest direction, and is estimated to be about three miles wide.

The Camp Swift area lies within the Mexia fault zone, which is traceable from Titus County near the Louisiana border to Medina County in the southern part of the state. This fault zone is closely associated with the Balcones fault zone, which occurs about 25 miles northwest of Camp Swift. The faulting is by normal faults, and the downthrow is generally to the west and northwest. The zone is extensively developed in Caldwell County, which adjoins Bastrop County on the southwest. Several faults have been reported east

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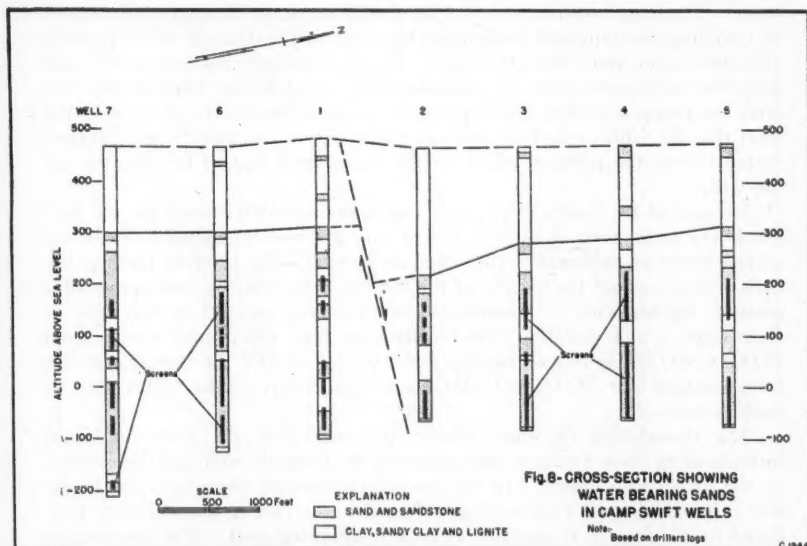


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and southeast of the camp area. A fault, which was first located by pumping tests of the wells at the camp, lies between wells 1 and 2. The vertical displacement as shown by a section based on drillers' logs (see Fig. 8) is approximately 100 feet. Although the trend of the fault has not been mapped, the downthrow is probably to the northwest.

Three series of pumping tests have been made of the wells supplying Camp Swift (12). The first series was made on two test wells during November, 1941, before the camp was constructed. It afforded enough information to warrant the conclusion that the sands drawn upon are fairly permeable and



would yield sufficient water to meet the needs of the camp as originally estimated, about 3.5 million gallons a day, without excessive drawdown of the water levels. However, the data obtained from this series of tests were not enough to predict accurately the drawdowns in the production wells, so two series of tests were made in June and July of 1942 on the first five production wells after they were finished, together with one of the original test wells. Each series of pumping tests was divided into two or more separate tests, each test consisting of starting or stopping the pump in one of the wells and observing the drawdown or recovery of the water levels in it and in the other idle wells of the group. Except for one short test conducted on test well 2, the lengths of the separate tests ranged from about 10 hours to 4 days and averaged about 2 days.

In the tests almost no effect was obtained on the water level in well 1 by pumping or shutting down any of the other wells, and, vice versa, the

pumping or shutting down of well 1 had practically no effect on the water levels in the other five wells. Therefore, it seems probable that well 1 is shut off, at least locally, from the other five wells by the fault.

The curves of drawdown and recovery of water levels obtained in the tests were analyzed by the non-equilibrium and Thiem formulas. The non-equilibrium formula, as used in these tests, was applied to the rate and amount of drawdown in a single well at different times during a test, and gave different coefficients of transmissibility and storage for different periods during each test except those of well 1. This was apparently due to the fault, which has the effect of increasing the rate and amount of drawdown or recovery in the wells. The length of time required for the effect of the fault to present itself by changing the computed coefficients depended on the distance of the pumped and observation wells from the fault. The two recovery tests of well 1 each gave the same coefficients of transmissibility for different intervals of time after the pump was shut down, probably because the well is so close to the fault that the fault's effect on the water level began too quickly to be differentiated from the primary effect on the water level caused by shutting off the well.

Because of the fault's effect, only the coefficients determined for the first few hours of the tests of wells 2, 3, 4, 5, and 2-T are considered to be in the correct order of magnitude—the other coefficients being in error because the fault is so close and the lengths of the tests so long that the assumption of a uniform aquifer with no boundaries over the area covered by the cone of depression is not fulfilled. The coefficients thus determined range from 37,000 to 87,000 for transmissibility and 0.0003 to 0.0007 for storage. It has been assumed that 45,000 and 0.0004 are conservative values which may be used as averages.

The drawdowns of water levels computed with the non-equilibrium formula using these averages were adjusted for both the fault and the outcrop by the image well theory. In the case of the outcrop boundary, the image well is assumed to be a recharging well, and in the case of the boundary produced by the fault it is assumed to be a discharging well. The discharging image well created by the fault is also reflected by a second recharging image well on the other side of the outcrop. Computations show that equilibrium of water levels should be reached about three months after the start of pumping, or after an increase in pumping.

From the adjusted computations, it was concluded that 600 gallons a minute is about all that can be pumped continuously from each of wells 2, 3, 4, and 5 without lowering the pump bowls, and that about 800 gallons a minute is about the maximum that can be pumped from each of the wells without dewatering the upper part of the aquifer. According to the figures, well 1 may be pumped at as much as 1,000 gallons a minute. Therefore, 4,200 gallons a minute, or about 6,000,000 gallons a day, is the maximum that theoretically should be pumped from the five wells.

Since the tests were made the average rate of pumping by months for the camp has ranged from 800 gallons a minute to 2,500 gallons a minute, and two additional wells have been installed in the line to the south of and on the

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same side of the fault as well 1. Owing to constant periods of pumping or to peaks and subsequent decreases in pumping, the water levels in the wells have been in equilibrium at several times during the period, when nearly all the water was coming from the outcrop and the water levels in the wells were not appreciably declining. Rough computations of the drawdowns of water levels

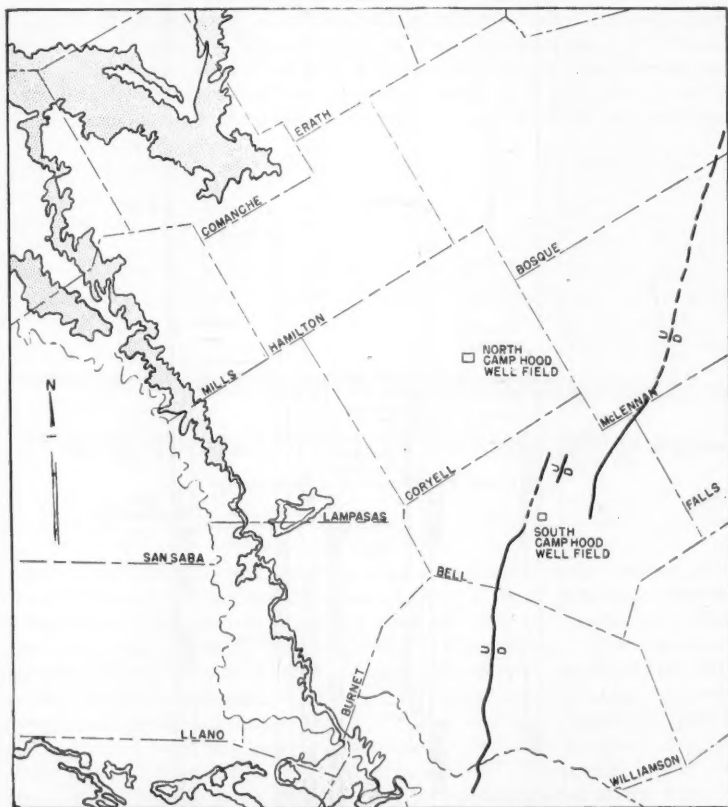
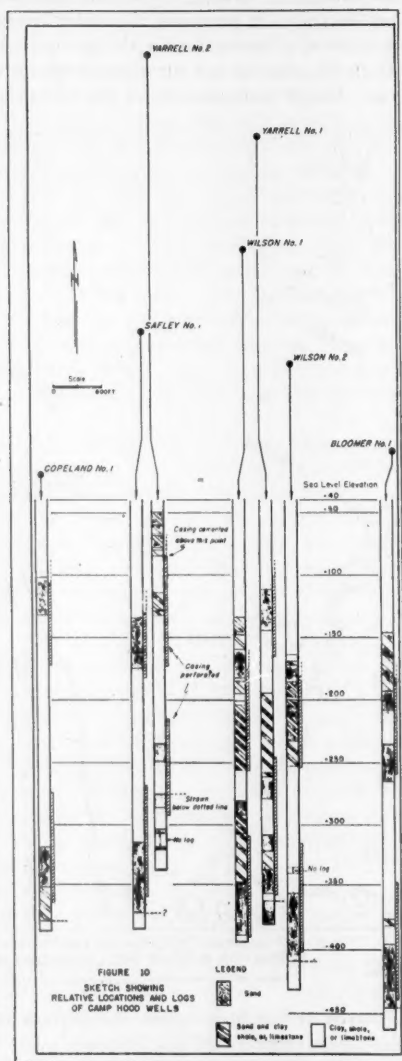


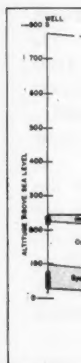
Fig. 9—MAP SHOWING OUTCROP OF THE TRAVIS PEAK FORMATION WEST OF THE CAMP HOOD AREA.

FROM GEOLOGIC MAP BY R.T. HILL, U.S. G.S. ANNUAL REPORT XIV, 1899

that should have occurred at the times when equilibrium was reached show computed drawdowns approximately 10 per cent too great for wells 2, 3, 4, and 5, and approximately 10 per cent too small for well 1. These figures indicate that either the average coefficients used are too small for the northwest side of the fault and too large for the southeast side, or that the fault is not continuous through the area. Possibly both conditions exist.



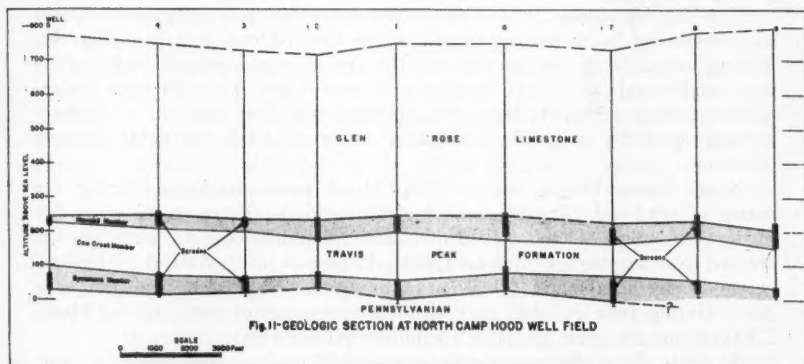
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*Camp Hood Area.* North Camp Hood and South Camp Hood are in Bell and Coryell Counties, and the two well fields supplying the camps are about 28 miles apart (see Fig. 9). The area lies within the Lampasas Cut Plain of the Grand Prairie physiographic province. The altitude ranges from about 500 feet above sea level in the valleys to about 1,200 feet on the highest ridge.

The source of the well water for both camps is the Travis Peak formation, of Lower Cretaceous age, which lies stratigraphically below the Glen Rose limestone and above the Strawn group, of Pennsylvanian age. The Travis Peak formation may be divided into three members in this area, but the correlation of the members between some of the wells at South Camp Hood is difficult (see Figs. 10 and 11). Although it is not definitely proven, these



members are probably the equivalents of the Hensell sand member, Cow Creek limestone member, and the Sycamore sand of Hill. The upper member is made up of fine- to coarse-grained sand and some sandy clay and sandy limestone, with the sandy clay frequently predominating. This member is generally rather uniform in thickness but quite variable in character. The middle member is composed of clay with varying amounts of sandy clay, very fine-grained sand, and limestone. The lower member consists of fine- to coarse-grained sand and gravel containing thin beds and lenses of clay and sandy clay. This member generally grades from coarse-grained sand and gravel at the base to fine-grained, loosely consolidated sand at the top. In general this member is variable in character, thickness, and extent. It is absent in Yarrell 2 well at South Camp Hood because of a topographic high on the old Paleozoic floor.

The thickness of the Travis Peak formation in the North Camp Hood well field ranges from 200 to 250 feet and in the South Camp Hood well field from 215 to 275 feet. In general the formation thickens eastward and becomes thinner westward, and in the westward extension of the formation toward the outcrop the lower sands are missing. Although the lower sands terminate against the Paleozoic floor somewhere between the well fields and

the outcrop to the west, they are believed to be connected in part to the upper sands there by a thin basal conglomerate which is present almost everywhere between the Travis Peak formation and the underlying floor.

The Balcones fault zone, which trends approximately north and south, is the major structural feature in the area. It occurs about 2 or 3 miles west of the South Camp Hood well field and about 20 to 30 miles southeast of the North Camp Hood field. Near the South Camp Hood well field the zone is represented by a flexure or increase in the dip of the formation, rather than by actual displacement of strata. In other parts of the area, faults are found in the zone with as much as 75 feet displacement, but they are local in extent and it is believed that they have little effect upon the movement of water through the Travis Peak formation.

The outcrop of the Travis Peak formation occupies an irregularly shaped area northwest, west, and southwest of the Camp Hood area (see Fig. 9). Throughout most of the outcrop area the formation consists of sand, gravel, and conglomerate with some sandstone, limestone and clay. In some places, however, the outcropping beds are indurated with lime cement. The nearest outcrop of the Travis Peak formation to either of the well fields is about 40 miles.

South Camp Hood. South Camp Hood was constructed during the spring of 1942 and the wells supplying it were first pumped in the early fall of the year. Since October 1942 the rate of pumping from the wells has increased from an average of about 1,300 gallons a minute, or about 1.9 million gallons a day, to about 2,100 gallons a minute, or about 3 million gallons a day. During June and July of 1943 the average rate of pumping was about 2,360 gallons a minute, or about 3.4 million gallons a day.

At first, six of the seven wells in the field had artesian heads of from 30 to 80 feet above the land surface, depending on the altitude of the surface, while the seventh well had a water level about 20 feet below the surface. After pumping was commenced, however, the water levels in the wells dropped rapidly, and by the first of October the water levels in all but one of the wells were below the surface. It could be seen that the levels were going to decline considerably more than anticipated, and the Army engineers asked the Geological Survey to make pumping tests of the wells to determine as nearly as possible just what the future drawdowns would be.

A series of eight pumping tests was made during October (13), each test consisting of starting or stopping the pump in one of the wells and observing the drawdown or recovery of the water levels in it and in the other wells in the field which were not being pumped. The lengths of the tests ranged from about 1 day to 7 days and averaged about 4 days. The rates at which the individual wells were pumped ranged from 300 to 500 gallons a minute.

After extraneous fluctuations of the water levels were eliminated, the drawdown and recovery curves obtained by pumping or shutting down individual wells were analyzed by the non-equilibrium and Thiem formulas. Except for the coefficients determined from tests of Yarrell 2 well in which the lower sands are absent, the coefficients of transmissibility and storage obtained from the analysis are fairly uniform. The coefficients involving

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Yarrell 2 well are omitted, therefore, in this discussion, for the pinching-out of the lower sands at that location is believed to be local. Twenty-two coefficients of transmissibility obtained with the non-equilibrium formula range from 6,900 to 11,600 and average 9,100. Seven coefficients obtained with the Thiem formula from tests with good alignment of wells range from 7,700 to 13,500 and average 8,600. The average coefficient of transmissibility accepted for the Travis Peak formation in the South Camp Hood well field is 8,800. The coefficients of storage range from 0.000023 to 0.000064 and average 0.000048.

The average coefficients of transmissibility and storage, 8,800 and 0.000048, respectively, were used with the non-equilibrium formula to compute drawdowns that should occur in the South Camp Hood wells during the first three years of operation. As described under the section on pumping tests, the one-day specific capacities of the wells, which range from 1.2 gallons a minute per foot of drawdown for Yarrell 2 to 5.5 for Bloomer 1, were used in these computations.

Because the outcrop of the Travis Peak formation is so far away from the well field, its effect on the drawdowns of water levels in the wells during the first three years of pumping probably will be negligible and was, therefore, not included in the computations. The thinning of the formation up-dip and the thickening down-dip will each affect the drawdowns, but for lack of more definite data, the best assumption that could be made to compensate for them is that the errors caused by one will counter-balance those caused by the other.

Using assumed rates of pumping from each well, with a total rate of pumping of 2,700 gallons a minute, the computed drawdowns of water levels in the wells at the end of three years of continuous pumping range from 370 to 425 feet. The drawdowns after three years and before equilibrium of water levels will be reached were computed to be small in proportion to these figures. These figures showed that the pump settings in the wells were not sufficiently low and that new pumps and motors would probably be needed in some of the wells before the end of three years.

Since the pumping tests were made, an accurate check has been kept by the Post Engineer of the pumpage from the wells and the water levels in them. New computations have been made of the drawdowns that should have occurred on April 30, 1943 and September 5, 1943, using the rates of pumping that were actually in effect before and at those times. On April 30, about eight months after the start of pumping, the actual drawdowns of water levels in six of the wells ranged from 234 to 295 feet. The computed drawdowns for that date range from 260 to 305 feet, the average error in the computed drawdowns being 5 per cent. The computed drawdowns for two of the wells are slightly too small and for four of the wells slightly too large. On September 5, about a year after the start of pumping, the actual drawdowns in the six wells ranged from 257 to 350 feet, while the computed drawdowns for that date range from 274 to 354 feet. The average error in the computed drawdowns for that date is 3 per cent. The computed drawdowns for four of the wells are too small, and for two of the wells too large. The close check shown by these figures is particularly fortunate in view of the



considerable variations from the assumptions of the formula used to compute the drawdowns.

**North Camp Hood.** At the request of the U. S. Engineers an investigation was made at North Camp Hood by the Geological Survey to determine the number and spacing of wells and the depths of pump settings in them necessary to produce the amount of water required for the camp. Three series of pumping tests were made. The first test, which was made in October 1942 on a test well, afforded enough information to conclude that the estimated camp requirements of 4,000,000 gallons a day could probably be withdrawn from the Travis Peak formation by 12 wells spaced about one-half mile apart. In November 1942 the estimated requirements were reduced to about 3,000,000 gallons a day, so it was decided that only nine wells would be installed. The nine wells were completed in February 1943. Pumping tests were then made of these nine wells to check the results of the first test, to obtain better data for computing future drawdowns of water levels, and to assist in locating additional wells (14). In February 1943 the estimates of water requirements for the camp were increased to 4,500,000 gallons a day, or 3,100 gallons a minute, and it was decided that the other three wells originally contemplated would be necessary to supply this increased demand. These wells were completed in June 1943 and pumping tests were subsequently made of them.

The second series of pumping tests consisted of eight separate tests, each test consisting of starting or stopping the pump in one well and observing the drawdown or recovery of the water levels in it and in two or three nearby wells. The lengths of the tests ranged from two to three days. The third series of tests was made of wells 10, 11, and 12 in a manner similar to those of the other wells, except that water-level measurements were made only of the recovery in the pumped wells.

The drawdown and recovery curves of the water levels obtained from these tests were analyzed by the non-equilibrium formula to determine the coefficients of transmissibility and storage. The 30 values for the coefficient of transmissibility computed from the curves range from 4,200 to 19,200 and average 10,700. The 22 values for the coefficient of storage range from 0.000036 to 0.000278 and average 0.000094. The probable explanation for the wide range in the values of the coefficients is that the sands of the Travis Peak formation are variable in character, thickness, and extent, that the lower member lies unconformably on the underlying formations and is probably not continuous over wide areas, and that two, and possibly three, of the wells do not penetrate the full thickness of the formation.

The one-day specific capacities of seven of the 12 wells were determined in the tests. They range from 1.5 gallons a minute per foot of drawdown for well 12 to 5.2 for well 1. Based on these figures and the logs and locations of the wells, the following schedule of pumping from the 12 wells was selected to give the total demand of 3,100 gallons a minute: wells 1, 2, 3, 4, and 10 are to be pumped at a rate of 300 gallons a minute each; wells 6, 7, 8, 9, and 11 at 250 gallons a minute each; well 12 at 200 gallons a minute; and well 5

at 150 gallons a minute. The selected rates for wells 5 and 12 are less than those for the other wells because of their low specific capacities.

The theoretical drawdowns of water levels in the wells after 3 months, 1 year, and 3 years of continuous pumping at a rate of 3,100 gallons a minute from the 12 wells were computed by the non-equilibrium formula. As in the case of the South Camp Hood figures, no adjustments were made for the outcrop or variations in thickness and character of the formation. Under the selected schedule of pumping the computed drawdowns in the 12 wells at the end of 3 years of continuous pumping range from 275 feet in well 1 to 357 feet in well 11 and average 308 feet. Pump settings were selected by the U. S. Engineers so that at the end of 3 years of continuous pumping the pump bowls in all the wells except 10, 11, and 12 will be from 25 to 70 feet below the computed pumping levels. According to the computations the pump settings chosen for wells 10, 11, and 12 will be low enough for efficient operation for only about 2 years.

*Sweeny Area.* The Sweeny area, which is in the western part of Brazoria County near the Old Ocean oil field, lies within the West Gulf Coastal Plain and is a smooth, nearly featureless plain that rises from sea level on the Gulf to about 32 feet at the town of Sweeny, approximately 20 miles inland. The principal aquifer in the area is a massive sand that is encountered at a depth of from 90 to 100 feet below the surface and averages about 60 feet in thickness. This sand, which will be termed the "100-foot sand," occurs in the upper part of the Beaumont clay, of Pleistocene age. The bed consists of fine- to moderately coarse-grained sand with thin layers and lenses of clay and sandy clay. The bed dips toward the southeast at an estimated rate of about 20 feet to the mile.

In February 1943 a pumping test was made of one production well and two test wells that penetrate this sand at the Aviation Gasoline Plant of the Abercrombie-Harrison Oil Company near Sweeny (15). The purpose of the test was to determine the amount of water that can be withdrawn from the "100-foot sand" in this area and, in particular, the number of wells and their spacing necessary to obtain 3,600,000 gallons of water a day for the gasoline plant.

In the pumping test the production well was pumped 44 hours at a rate of 500 gallons a minute while the drawdowns in the well itself and in the two observation wells, located at distances of 400 and 1,100 feet from the production well, were observed. After the pump was shut down the recovery of the water level in the three wells was observed for 72 hours. The specific capacity of the production well was found to be about 15 gallons a minute per foot of drawdown.

The drawdown and recovery curves of the water levels obtained from the test were analyzed by means of the Thiem and non-equilibrium formulas. The coefficients obtained by the Thiem formula were 34,300 and 34,900, while the coefficients obtained by the non-equilibrium formula ranged from 36,200 to 41,500 and averaged 39,100. The coefficients of storage ranged from 0.000318 to 0.000474 and averaged 0.00039.

Assuming that 38,000 and 0.00039 are the approximate average values for the coefficients of transmissibility and storage and that the outcrop of the "100-foot sand" is about five miles northwest of the center of pumping, the theoretical drawdowns of water levels produced by several arrangements of wells and rates of pumping after continuous pumping for 3 months, 1 year, and 3 years, were computed by means of the non-equilibrium formula. The results showed that the most economical spacing of the wells would be about 2,500 feet apart and that the most practicable rate of pumping from each well

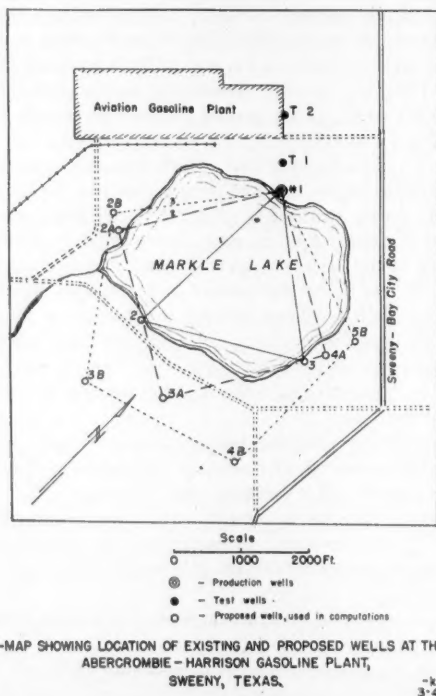


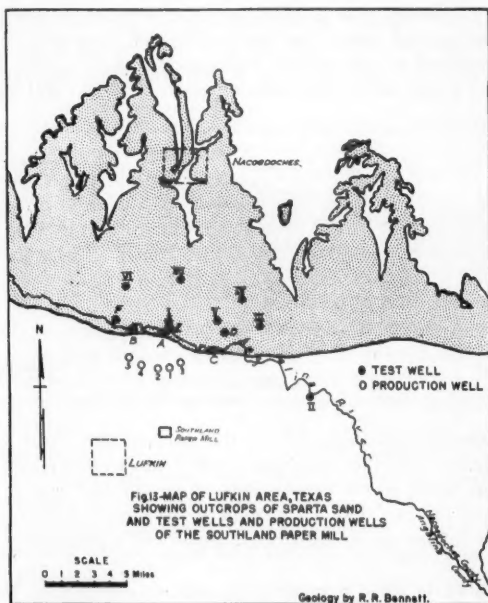
Fig. 12-MAP SHOWING LOCATION OF EXISTING AND PROPOSED WELLS AT THE ABERCROMBIE-HARRISON GASOLINE PLANT, SWEENEY, TEXAS.

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would be about 500 gallons a minute. Based on these figures three plans for pumping were assumed (see Fig. 12): (1) 500 gallons a minute from each of three wells (nos. 1, 2, and 3); (2) 500 gallons a minute from four wells (nos. 1, 2a, 3a, and 4a); and (3) 500 gallons a minute from each of five wells (nos. 1, 2b, 3b, 4b, and 5b). The arrangement of the wells as shown on the map was chosen because the Abercrombie-Harrison Company proposes to pump the water from the wells into Markle Lake. The pumping levels computed for the wells after 3 months of continuous pumping under plan 1 are about 70 feet below the land surface, under plan 2 about 77 feet, and

under plan 3 about 85 feet; and after 3 years of continuous pumping under plan 1 they are about 72 feet, under plan 2 about 80 feet, and under plan 3 about 91 feet.

Conditions are apparently favorable in the vicinity of the gasoline plant for the withdrawal of water from the "100-foot sand" at a rate of 2,000 gallons a minute, or about 3,000,000 gallons a day, from four wells producing 500 gallons a minute each and spaced about 2,500 feet apart around Markle Lake. However, if 2,500 gallons a minute, or about 3,500,000 gallons a day, is withdrawn from the aquifer as outlined in plan 3, no margin of safety will be allowed and the unwatering of the sand might begin soon after the start of

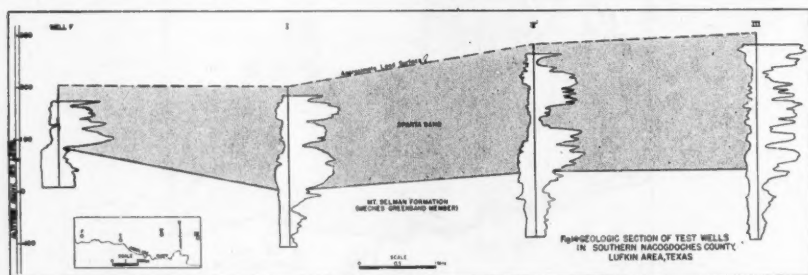


pumping. This would cause a reduction in the transmissibility of the aquifer and greater drawdowns in the wells. The water requirements in excess of 2,000 gallons a minute, therefore, should be obtained from lower sands that contain water of higher mineral content. In accordance with these conclusions the Abercrombie-Harrison Oil Company has recently drilled four wells to the "100-foot sand" as outlined in plan 2 and two wells to the lower sands.

*Lufkin Area (Sparta Sand).* An investigation has been made of the possibilities of obtaining a water supply at Lufkin from the Sparta sand of Eocene age. The Sparta sand, which is overlain by the Cook Mountain formation and underlain by the Weches greensand member of the Mount Selman formation, all of Eocene age, crops out in Nacogdoches County, just

north of the Angelina River (see Fig. 13). The southern boundary of the outcrop is about three miles north of the paper mill's wells obtaining water from the Carrizo sand. The outcrop forms a belt of moderate relief that varies in width from about 3 to 15 miles. The formation dips to the south at the rate of about 40 feet to the mile.

In 1940 two test wells were drilled by the paper mill at each of three locations just south of the Angelina River (A, B, and C locations). In 1941 eight wells were drilled on the outcrop area, and a ninth just south of the outcrop (locations I to VII). From the drilling and studies of the outcrop it was found that the Sparta sand consists of very fine- to medium-grained sand with lenses and beds of clay and sandy clay. The very fine-grained sand varies widely in amount and distribution, and because of this irregular distribution the amount of water that can be obtained from wells in this formation may be expected to vary widely from place to place. The thicknesses of the Sparta sand found in the test wells range from 120 to 260 feet, depending



mainly upon stratigraphic position of the surface elevations of the wells. Analyses of water from the wells and studies of electrical logs in the area indicate that the water in the Sparta sand at its outcrop, and at some places just south of the outcrop, has a low mineral content, but that it has a high mineral content further south toward the paper mill's production wells in the Carrizo sand.

In the summer of 1942 a production well was drilled in the Sparta at location E and screened in approximately the lower half of the sand, which is separated from the upper half by a thin clay bed. A pumping test was made of this well, and at the end of one day of pumping the well was found to have a specific capacity of only a little over one-half gallon a minute per foot of drawdown. Observations of water levels in this well during and after the pumping, and in a test well 400 feet to the north, were analyzed by the non-equilibrium formula; and a coefficient of transmissibility of about 1,000 was obtained. No large amount of water could be obtained economically from the Sparta sand if the transmissibility and specific capacities were generally as low as obtained in this test. However, studies of drill cuttings and the outcrop show that the lower half of the Sparta is in general considerably finer than the upper, and it, therefore, is believed that this test was not repre-

sentative and should not be accepted as conclusive evidence that the formation is unproductive.

In the summer of 1943 three additional production wells and observation wells were drilled in the Sparta just north of the Angelina River (locations D, E, and F), and pumping tests were made of them. (The additional wells at location E were screened only in the upper part of the sand which was not included in the test made in 1942.) The data obtained from the tests were analyzed by the non-equilibrium formula. The coefficients of transmissibility computed range from 11,000 to 34,000 for the tests at location D, from 2,200 to 4,200 for the tests at location E, and from 44,700 to 58,100 for the tests at location F. The coefficients of storage range from 0.00017 to 0.0028, 0.00026 to 0.00052, and 0.00038 to 0.00047, respectively. The specific capacities of the production wells were about 3.1 after one hour for location D, 1.1 after two days for location E, and 7.5 after one day for location F.

These data show that the Sparta sand varies widely in its capacity to yield water to wells. Estimates of drawdowns of water levels based on the data obtained from the tests and studies of recharge indicate that the Sparta might be developed economically in some places and not in others. It is estimated that not over 200 gallons a minute should be expected from the average well, and that the spacing of wells of this capacity should be at least 2,000 feet.

#### SUMMARY.

Since 1939, pumping tests and their application have come into general use in Texas. At first they were considered too theoretical and impractical, but as they have been tried and developed more they have been found to be an exceedingly valuable addition to the methods used in ground-water investigations. They should, however, be used carefully and in connection with other methods wherever possible. Since a water-bearing formation is never as regular in character, thickness and extent as it is assumed to be by the formulas, its geology should be thoroughly investigated before the results of pumping tests are applied to determining drawdowns. The reliability of the results depends very largely upon how well the geology agrees with the assumptions of the formulas.

As the formulas are revised and new ones developed so that it becomes possible to take more of the geologic and hydrologic variations into account, the use and value of pumping tests and their application will become even greater than at present. To this end, new methods of making and analyzing tests and applying the results should be publicized as much as possible. Ground-water problems should be studied more by mathematicians and physicists; and the allied fields of petroleum and soil mechanics should be searched for methods and data which may apply to ground water.

February, 1944.

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## DISCUSSION AND COMMUNICATIONS

### ORE MINERALS OF THE LA PLATA MOUNTAINS, COLORADO, COMPARED WITH OTHER TELLURIDE DISTRICTS.

(The following discussion was written from the Philippines shortly before Pearl Harbor. Latest report indicates that Mr. Schafer and his family are safe and presumably will soon be repatriated. Editor.)

*Sir:* In an article by F. W. Galbraith on the telluride ores (*ECON. GEOL.*, vol. 36, pp. 324-334, 1941), he gives a sequence of mineral deposition which in part is as follows:

"3. Vein sulphides in the following order:

- a. pyrite
- b. sphalerite and chalcopyrite
- c. tetrahedrite
- d. galena
4. tellurides . . .
5. native gold."

This is called a "general sequence" because reversal of sequence occurs in some specimens. The writer says:

"Thus, in some specimens the later fine-grained generation of pyrite surrounds and embays grains of sphalerite, veinlets of chalcopyrite cut through tetrahedrite, and sphalerite has replaced galena along grain boundaries and cleavage traces (Fig. 1), suggesting a close time relationship between the formation of the different minerals and an overlap in the sequence of deposition."

Thus nearly any sequence or a variety of sequences may be constructed from the description; but the most frequent relationships are used and the less common conditions are assumed to be overlaps and to represent a close time relationship in the deposition of the different minerals. This is a customary procedure in determining mineral sequence and has the approbation of a great body of literature on paragenesis. But may we inject a word of caution regarding the basis on which such conclusions are reached.

At Neihart, Montana, where fissure veins contain complex silver and gold ores associated with high base metal content, I found reversals of mineral sequence in many mineral sections. In some cases the sequence (1) chalcopyrite and tetrahedrite, (2) sphalerite, (3) galena, (4) silver minerals and gold, was apparent, but in others the reverse, at least in part, was found with (1) galena, (2) sphalerite, and (3) chalcopyrite. It was found that the sequence was determined by the structural peculiarities of the veins. At Neihart, as in many Colorado districts, the veins are compound: consisting of a dominant massive base metal portion in which silver and gold content is low, and one or more streaks of high grade material in crustified layers and drusy

cavities. The latter may fill breaks in the earlier material or it may simply comprise the central part of the vein. My description of the mineral relationships follows:

"The order of sequence of deposition has been determined for most of the vein minerals in the Neihart district. This was done in two ways: by microscopic examination of polished specimens and by a study of the sequence of crusts or layers in the crustified ore. All minerals appear to occur twice in the succession; once in the massive ore and again in crusts and druses. In general, the sequence in the massive ore is reversed in the crustified ore. Whereas quartz and pyrite are among the earliest minerals in massive ore, they are among the latest in the druses. . . .

Not everywhere is the complete succession apparent. Each mineral replaces to a greater or less extent the minerals which precede it in the series. The ease of replacement varies widely with different combinations of minerals; some are more vigorously attacked than others by replacing processes. Thus, quartz and pyrite are more difficult to replace than galena; and if sphalerite is being deposited, it has a tendency to replace galena more readily than those minerals (quartz and pyrite). Therefore, galena remains as a remnant of early deposition less commonly than quartz and pyrite. Similarly, any early silver or carbonate minerals are very susceptible to replacement by a host of later minerals. In this way any apparent sequence may be only partially complete, much evidence having been obliterated by replacement.

Seldom are all of the late minerals found in the crustified ore. Here again, the sequence is rarely complete on account of certain structural peculiarities. For example, complete vein filling may have been achieved in certain portions of a fissure before the latest minerals could be deposited, or openings may have been so large that mineral deposition failed to fill them," [in which case the complete sequence would be present]. To a large extent, "the same minerals comprise late-stage filling and the (earlier) massive ore, but [they] usually occur in the reverse order of deposition. Replacement is not important in late-stage ore, as it is in the massive ore."<sup>1</sup>

The sequence of minerals is a double one:

Early stage (Massive replacement ore)	Late stage (Crustified ore)
1. Quartz and carbonates	1. Chalcopyrite
2. Pyrite and arsenopyrite	2. Tetrahedrite
3. Silver sulphides and gold	3. Sphalerite
4. Galena	4. Galena
5. Sphalerite	5. Silver sulphides and gold
6. Tetrahedrite	6. Pyrite
7. Chalcopyrite	7. Quartz and carbonates

It was assumed that the early stage ore was deposited during a period of building up of heat in the fissure by the passage of solutions, causing the deposition of successively higher-temperature minerals with intense replacement and the consequent *displacing* of pre-existing minerals up the channel-way.

At a certain point the temperature must begin to decline due to loss of heat at the source, constricted channels slowing up the speed of flow, or other causes. Then crust on crust of successively lower-temperature minerals are deposited. Because replacement is slight, the maximum concentration of precious constituents can be achieved.

<sup>1</sup> Schafer, Paul A.: Geology and ore deposits of the Neihart mining district, Cascade County, Montana. Montana Bureau of Mines and Geology, Memoir 13, 1935, p. 21.

Impressed by the idea that age relations of galena, sphalerite, and chalcopyrite, which often show "mutual boundaries," might be misconstrued, and impelled by the reports of early sphalerite and late copper minerals at Butte and other places in complete disagreement with the facts of zoning, as indicated recently by Hart,<sup>2</sup> I examined a large number of specimens from Butte, Phillipsburg, and other localities. In all cases the double sequence was apparent, at least in part. Sphalerite replacing galena was found, but in many cases the abundance of sphalerite and copper minerals, to the exclusion of galena, suggested that galena may have been eliminated by complete replacement.

Granting that such a process of ore deposition exists, as outlined above, then the changes of temperature (funneling of isotherms up the channelway) would depend on permeability and source depth, and only deposits with shallow source depths and high permeability would possess the early stage succession. Deposits formed from deep sources are most likely to contain minerals precipitated during gradually decreasing temperatures. For that reason Galbraith's comparison of Colorado telluride ores with those of the Canadian shield is intensely interesting. Apparently the *intensity factor*<sup>3</sup> is the same for both, although it is probable that the source depth is far greater for the Canadian ores than for those of Colorado.

He mentions no reversals of the "normal" sequence in the Canadian ores; indeed it is probable that all minerals were deposited during a gradually falling temperature at any point along the channelway. Therefore, although the mineralogy may be identical, one group may fall in the depth range usually designated as epithermal, while the depth range of the other may be considered mesothermal or even hypothermal. Perhaps we have put too much emphasis on the idea of parallelism of depth and temperature and not enough on the importance of permeability in causing upward migration of isotherms.

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<sup>2</sup> Hart, L. H.: A theory of mineral sequence in hypogene ore deposits—a discussion. *ECON. GEOL.*, vol. 35, 1940.

<sup>3</sup> Graton, L. C.: The depth-zones in ore deposition. *ECON. GEOL.*, vol. 28, p. 521, 1933.

## REVIEWS\*

**Handbook of Mineral Dressing; Ores and Industrial Minerals.** Edited by ARTHUR F. TAGGART. Pp. 1915; Figs. 1353; Tables 873. John Wiley & Sons, New York, 1945. Price, \$15.00.

The most recent of the Wiley engineering handbook series, *Handbook of Mineral Dressing* enters the field at a time of important advancements in methods of concentration of metalliferous ores. As our mineral reserves are seriously exploited by war-time demand, native deposits of marginal value as well as foreign deposits will be looked to as valuable aids in post-war reconstruction. In the establishment of new ore localities and in prolongation of existing camps thorough knowledge of mineral dressing processes becomes essential. In all cases, study of methods employed in other regions may be of greatest value. "Technical operations, even the least complex, involve numerous components and conditions that are not only indefinable but are frequently not even recognized as present. Under such circumstances prediction [of expectable performance] is possible only by study of similar technology, in which there are present essential controlling conditions that parallel those in the case in question. It is the purpose of a handbook to record such illustrative practices and to point out what appear to be the controlling conditions."

This handbook contains a thorough treatment of all phases of mineral dressing. Seventeen sections are devoted to ore treatment and allied subjects. The introductory sections deal with metallic minerals, industrial minerals and cement. The sections on minerals include discussion of uses, production, treatment, and selling. Production tabulations are through 1938. This part of the book will be valuable to all geologists interested in mineral statistics. Sections on mathematics complete the volume.

*Handbook of Mineral Dressing* is based on *Handbook of Ore Dressing* by the same editor and published in 1927. Several new sections have been added and the bulk of the other sections rewritten. Thirteen contributors have taken part in the present work. The editor is planning a second volume for this handbook. It is to treat the "preparation of fuels and of the methods, mostly chemical, by which metalliferous and non-metallic concentrates are rendered into primary-consumer products.

RALPH E. DIGMAN.

**Principles of Physical Geology.** By ARTHUR HOLMES. Pp. 532; Pls. 95; Figs. 262. The Ronald Press, New York, 1945. Price, \$4.00.

Professor Holmes has here given us a thoroughly up-to-date book on physical geology. It is intended as an introductory text in geology. As such the material has been well selected and presented in a lucid and interesting manner. It may be considered by some that topics such as isostasy, continental drift, cause of vulcan-

\* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

ism, etc. should not be included in elementary texts on geology. The treatment here is not over-technical. The author believes that a discussion of the fundamentals of geological problems still in the realm of speculation is of immense value to beginning students. In this belief many others concur.

The book is divided into three parts: preliminary survey, external processes and their effects, and internal processes and their effects. The chapters on rocks and rock minerals are unfortunately short. Numerous illustrations accompany the text. They are well selected but the halftones are very poorly reproduced. The book is an excellent treatment and will be a valuable addition to geological libraries. As a textbook it should be widely adopted in British schools and may find some use in America.

R. E. D.

#### BOOKS RECEIVED.

RALPH E. DIGMAN.

**Instituto de Fisiografía y Geología, Rosario, Argentina, 1944.**

**Consideraciones Generales Sobre los Terrimotos de la Argentina.** PIERINA PASOTTI. Pp. 50; Figs. 20. Pub. XX.

**Anotaciones Preliminares con Motivo de una Visita a la Ciudad de San Juan; a Proposito del Terrimoto del 15 de Enero de 1944.** A. CASTELLANOS. Pp. 145; Figs. 117; Pls. 6. Pub. XXI.

**Punta de Flecha Ósea Descubierta en el Pampeano Medio del Arroyo Saladillo (Rosario, Santa Fe).** A. CASTELLANOS. Pp. 32; Figs. 13. Pub. XXII.

**Cronica Bibliografica.** A. CASTELLANOS AND P. PASOTTI. Pp. 85.

**The Mineralogy of the Tin Mines of Cerro de Llallagua, Bolivia.** S. G. GORDON. Pp. 78; Figs. 82; Pls. 12. Vol. XCVI, The Academy of Natural Sciences of Philadelphia, 1944.

**Lavabilidade de Carvões do Brasil.** T. FRASER AND A. ABREU. Pp. 185; Figs. 24. Boletim 13, Departamento Nacional da Produção Mineral, Rio de Janeiro, 1943.

**Bibliografia e Indice da Geologia do Brasil, 1641-1940.** D. IGLESIAS. Pp. 323. Boletim 111, Departamento Nacional da Produção Mineral, Rio de Janeiro, 1943.

**El Departamento de Petróleo en 1943, Campo do Zorritos (Tumbes).** Pp. 162; Figs. 9; Pls. 11. Boletim 129, Cuerpo da Ingenieros de Minas del Peru, Lima, 1944.

**Cuadernos de Mineralogía y Geología.** Pp. 72; Figs. 4. Pub. 359, Universidad Nacional de Tucuman, 1944.

**Geología del Sureste de Venezuela.** V. LÓPEZ AND OTHERS. Pp. 28; Figs. 4. Pub. 49, Caracas, 1943.

**La Lithologie Graphique. Ses Applications a l'Etude Geologique du Katanga (1).** A. JAMOTTE. Pp. 14; Figs. 10. No. 6, Assoc. des Ingénieurs de la Faculté Technique du Hainaut, à Mons, 1944.

**Sur un Principe de Mobilité de l'emanation ourde l'intrusion Granitiques.** A. JAMOTTE. Pp. 2. 1940. Note sur la Probabilité de l'existence d'algues

- fossiles du Genre *Collenia* dans la Serie des Mines du Katanga. Pp. 3. 1941. Nouvelles Observations sur la Presence d'organismes du genre *Collenia* dans la Serie des Mines. A. JAMOTTE. Pp. 4; Figs. 4. 1941. Sur la decouverte de *Collenia* sp. dans le Systeme Schisto-Dolomitique et sur le Probleme de la Serie des Mines du Katanga. A. JAMOTTE and P. Brande. Pp. 9; Figs. 6. 1941. Notes complementaires sur la stratigraphie de la Serie des Mines et sur *Collenia* sp. A. JAMOTTE. Pp. 11; Figs. 3. 1943. Comite Special Du Katanga, Elisabethville, 1944.
- Geology and Mineral Deposits of the Red Lake Area.** H. C. HORWOOD. Pp. 230; Figs. 48; 13 geological maps in separate map case. Vol. XLIX, Part II, 1940, Ontario Department of Mines, Toronto, 1945.
- Washington Geological Survey.** Pullman, 1943.
- Report of Investigations No. 8. The Buckhorn Iron Deposits of Okanogan County, Washington.** W. A. BROUGHTON. Pp. 20; Figs. 4. Price, 25 cents.
- Report of Investigations No. 10. The Blewett Iron Deposit, Chelan County, Washington.** W. A. BROUGHTON. Pp. 20; Figs. 2. Price, 25 cents.
- Report of Investigations No. 11. Stratigraphic Aspects of the Blewett-Cle Elum Iron Ore Zone, Chelan and Kittitas Counties, Washington.** R. L. LUPHER. Pp. 63; Pls. 2. Price, 25 cents.
- Report of Investigations No. 12. Economic Aspects of the Blewett-Cle Elum Iron Ore Zone, Chelan and Kittitas Counties, Washington.** Pp. 42; Figs. 14; Pls. 7. Price, 25 cents.
- Biennial Report.** E. L. CLARK. Pp. 94. Missouri Geological Survey, Rolla, 1945.
- Pennsylvania's Mineral Heritage.** Pp. 248; Figs. 29. Pennsylvania Geological Survey, Harrisburg, 1944.
- Geology and Mineral Resources of the Burkes Garden Quadrangle, Virginia.** B. N. COOPER. Pp. 290; Figs. 11; Pls. 21. Bulletin 60, Virginia Geological Survey, University, 1944.

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## SCIENTIFIC NOTES AND NEWS

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DR. VICTOR M. LOPEZ, Director of the Venezuelan Government's Mining and Geological Service, has been decorated by the Government of Haiti with the Order of Petion-Bolivar in recognition of valuable services recently rendered. This decoration has hitherto been awarded to only seven other persons. He recently returned to Venezuela after a brief trip to the United States.

DR. GEORGE SWITZER, instructor in mineralogy in Yale University but now on leave, has taken the position of head of the crystal engineering division of Majestic Radio and Television Corporation, Chicago.

QUENTIN SINGEWALD has left Colombia for a brief trip to Venezuela on business for the Metals and Minerals Division of F.E.A. before returning to Washington.

DON SMYTHE has arrived in Liberia on duty for the F.E.A. Later he will join David Sharpstone in S. Africa.

MR. C. E. PETERSON has gone to London and Portugal in relation to tin procurement for the F.E.A.

GEORGE HEIKES has resigned from the War Production Board and is in the employ of Ventures Limited, temporarily stationed in Washington.

PHILIP D. WILSON has resigned as Vice-Chairman in charge of minerals of the War Production Board.

CARLTON HULIN, who is in China for the Metals and Minerals Divisions of the F.E.A., will return to India in the early summer.

EARL IRVING has returned from F.E.A. field duties in Central America and has joined the Washington staff of the Metals and Minerals Divisions.

HORACE FRASER, Assistant Chief of Metals Division, F.E.A., has returned from Cuba where he was investigating manganese and chrome.

PAUL TYLER of the Bureau of Mines is now one of the staff of the American Mining Congress.

ROBERT DONALD has gone to British Guiana to investigate columbite deposits for the F.E.A.

OLAF P. JENKINS, chief geologist of the California State Division of Mines, is chairman of the Reconstruction and Reemployment Commission's areal mapping committee in Sacramento.

SAMUEL LASKY of the U. S. Geological Survey is now studying the Silver City region, New Mexico.

E. N. PENNYBAKER has been studying the titanium deposits at Tahawus, New York, and is now at Miami, Arizona.

VINCENT D. PERRY has been made Assistant Chief Geologist in charge of outside examination work for the Anaconda Copper Company.



A. E. CAMERON, Deputy Minister of Mines of Nova Scotia, has been elected President of the Canadian Mining Institute, succeeding A. A. Mackay.

W. T. ROESLAER, geologist of the Auanchaca Mine, Bolivia, has resigned and returned to Los Angeles.

FRED JOHNSON, Chief Engineer, quartz program, of the F.E.A. in Brazil, has resigned to take charge of barite mining in Baia, Brazil.

ROBERT BUTLER in charge of the F.E.A. quartz program in Brazil, returned to Washington for conferences on the 1945 quartz program.

C. A. MITKE, who with Mrs. MITKE was released from San Tomas prison camp, Manila, reports he is in good health and ready to carry on war minerals work in the Philippines.

A. A. LEVORSEN has been appointed chairman of the Department of Geology of Stanford University, beginning next September.

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